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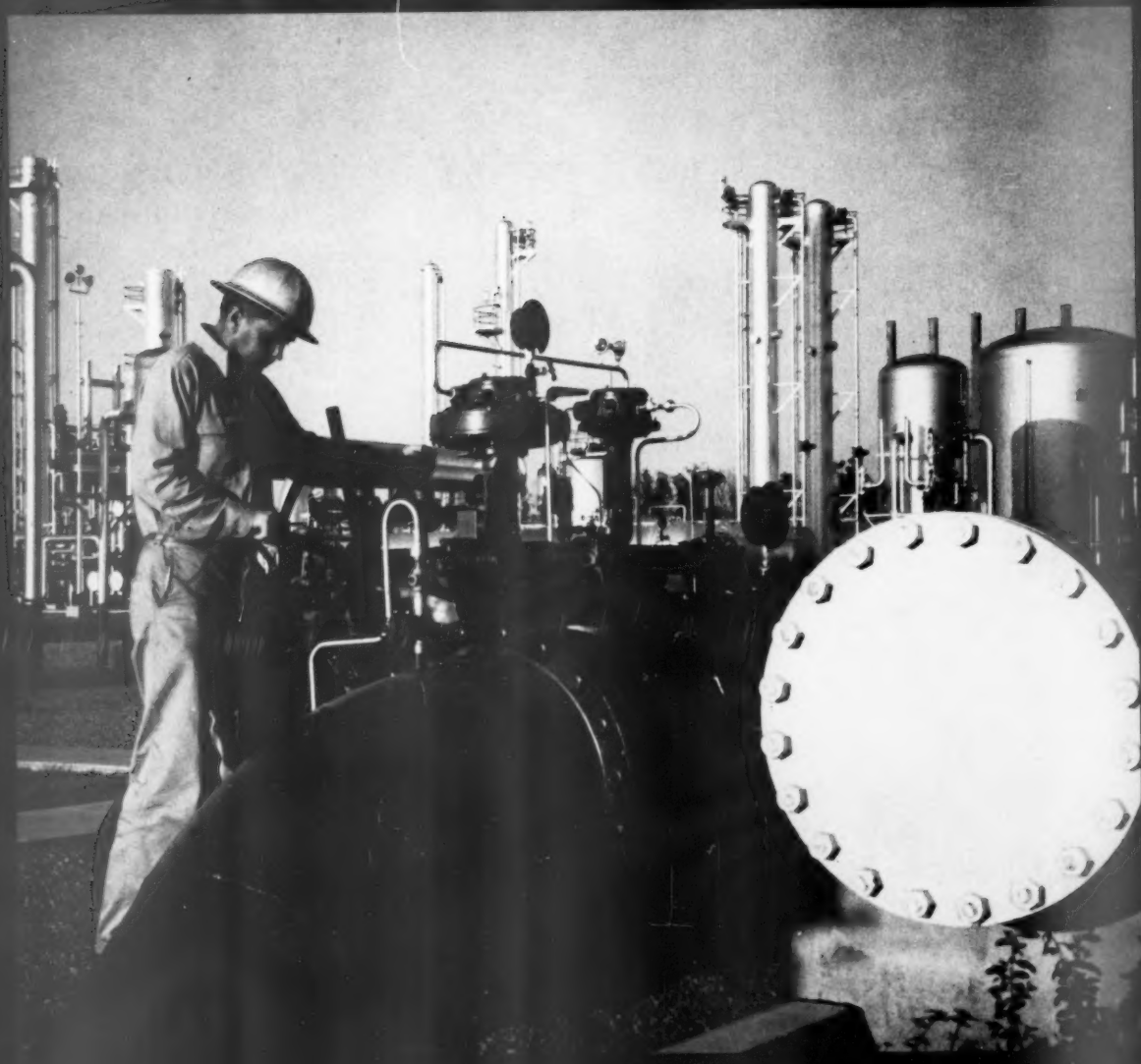

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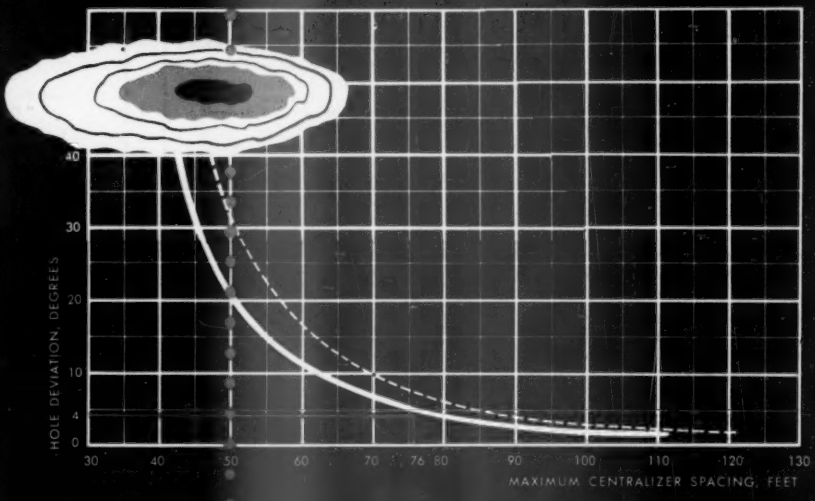

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Journal of Petroleum Technology is published monthly. Domestic Subscription: North, South and Central America, $8; foreign, $9; to AIME members, $6, or $4 if in combination with subscription to either Journal of Metals or Mining Engineering. Single copies 75 cents; special issues, $1.50. Registered cable address AIME. Printed in USA. Copyright 1951 by American Institute of Mining & Metallurgical Engineers.

Official Publication

Petroleum Branch

American Institute of Mining & Metallurgical Engineers

Statements and opinions contained in the JOURNAL are, unless otherwise indicated, attributable only to the author, and do not necessarily reflect the views of the AIME, its officers, committees, or other agencies.

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THE PROFESSIONAL MAGAZINE FOR PETROLEUM ENGINEERS

Journal of Petroleum Technology

Vol. III AUGUST, 1951 No. 8

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On the Cover — These large clusters of equipment are an inlet casing-head gas line and block valve installed adjacent to the Conroe Gas Plant in Montgomery County, Tex. The plant may be seen in the background. Here is processed casinghead and gas-well gas produced in the Conroe Field.

Photo courtesy Humble Oil and Refining Co.

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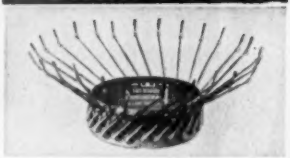

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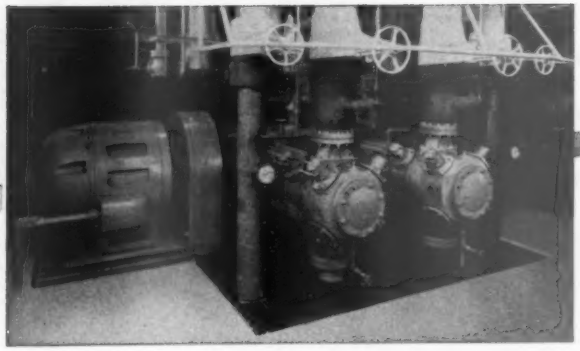

Clark CMA-4, 300 bhp, 600 rpm, balanced/opposed motor-driven compressor performing two compression services at Spencer Chemical Co. dry ice plant: Two cylinders in main or liquefaction service compress carbon dioxide through two stages from a suction pressure of 20 psig to a discharge pressure of 345 psig, and two cylinders in recycle service compress carbon dioxide two-stage from 0 psig to 345 psig discharge pressure.

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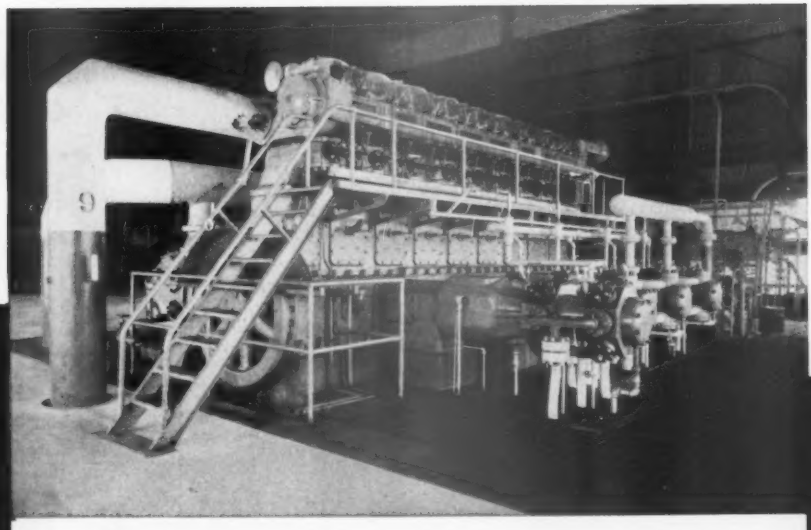
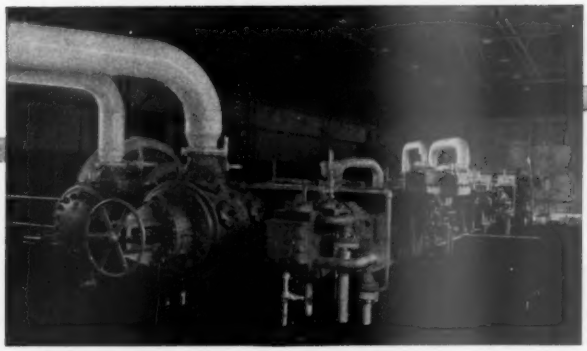


One of nine Clark SCRA, 2750 bhp, steam-engine-driven compressors, handling feed gas for ammonia manufacture at Spencer Chemical Co. Compression through six stages is from atmosphere to 5500 psig discharge pressure.



Two Clark CRA-6, 1750 bhp, 327 rpm, balanced/opposed motor-driven compressors, compressing hydrogen and carbon monoxide feed gas from atmospheric pressure to a discharge pressure of 5150 psig at Spencer Chemical Co. End product: Methanol.

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Today's NATURAL GAS INDUSTRY

Although Still a Young Industry, Natural Gas Has Steadily Gained Importance With Increasing Household And Industrial Use. Here, One of Today's Experts Reviews Its Progress and Current Economic Problems.

By Harold L. Hensley
Humble Oil and Refining Co.

INTRODUCTION

The natural gas industry as we know it today is in a healthy and vigorous state. And yet, it is still a young industry — an industry that is growing steadily and surely in stature and importance, but one which even yet has not attained its maturity. It is not possible to foresee definitely the ultimate toward which the industry is approaching. This, however, is reasonably certain: If the industry is allowed to expand and grow in the atmosphere of free and open competition in which it has so far developed, adequate supplies of natural gas will continue for many, many years to be found and made available at reasonable prices to the public and to industry in general. Under such conditions, natural gas ultimately will be able to attain its rightful position of importance in the nation's industrial and economic structure.

HISTORICAL BACKGROUND

To understand and appreciate the accomplishments of the industry, and to realize the impact exerted today by natural gas on the fuel and industrial economy of our country, it is well to know something of its history of development.

The occurrence of natural gas as seepage from the earth's surface was noted in certain areas of the Appalachian region of the United States as early as the explorational and colonial periods of our history. Early in the 1800's, natural gas had been encountered in the drilling and excavating of shallow water-wells. It was not until 1820, however, that a well was drilled purposely for the production of gas. This first well was located near a gas-seepage on the bank of a small creek in the town of Fredonia, N. Y., and was drilled to a depth of 27 ft. From this well came the supply of natural gas to be utilized commercially for the first time. In 1821, a small line of lead pipe began providing a gas-supply to nearby consumers for the purpose of illumination.

Limited commercial use of natural gas for domestic and industrial purposes followed closely in the wake of expanding prospecting for oil after its discovery in 1859 by the famous Drake well in Pennsylvania. A manufacturing plant in Erie, Pa., was using natural gas for fuel purposes in 1868, and by 1873 several iron and steel plants in the Pittsburgh district were making the same application. It was not until 1883, however, when gas was piped from Murrysville, Pa., to Pittsburgh, that the natural gas industry became firmly established. This same Murrysville Field was the site, in 1890, of the first successful application of compression to the transportation of natural gas by pipe line.

The prospecting for oil expanded rapidly in the 1860's, bringing with it the occasional completion of a well which produced strictly gas, with no oil. Such production was termed, simply, "natural gas." The gas produced in conjunction with oil was named "casinghead gas." It was observed that the flowing of oil wells producing casinghead gas usually resulted in the precipitation at the surface of a relatively volatile liquid called "natural" or "casinghead gasoline." In the transmission of casinghead gas through pipe lines, a similar precipitation had been noted.

In these earlier days of the industry, this liquid was strictly a waste product. Kerosene, or "coal-oil," was the product from crude oil most in demand for heating and lighting purposes, and for general utility it was necessary to remove the lighter gasoline fractions. However, with the advent of the automobile about the turn of the century, there began to be created a demand for gasoline. Larger quantities of gasoline were salvaged from the distillation of crude oil in the refineries, and the "natural" or "casinghead gasoline" contained in natural gas began to receive attention.

It was not long thereafter before it became known that the application of pressure to casinghead gas, in conjunction with cooling, resulted in increased recovery of gasoline. By 1908, the first successful compression plant of appreciable size had been placed in operation in West Virginia. By 1912, there were 250 such plants in operation, and in 1920 the total had increased to 967. This, however, was the peak year in the number of compression plants in operation, and there began, at about that time, a marked decline in the prevalence of such plants in favor of those applying the oil-absorption process. This trend continued through subsequent years until, at present, the strictly compression-type plant is practically nonexistent.

FACTORS OF RECENT GROWTH

These early efforts by the industry indicated, in a limited way at least, recognition of the potential usefulness of natural gas. The growth of the industry through the years, however, has been somewhat erratic. Prior to 1925, the markets for natural gas for domestic and industrial consumption were limited, and usually were confined to areas near the fields of production. Much of the casinghead gas, after having been stripped of its liquefiable components by processing through gasoline plants, was flared to the atmosphere. Large numbers of gas wells were allowed to remain shut-in for lack of markets. But with the advent of oxyacetylene welding and accompanying improvements in seamless carbon-steel pipe, there was begun, in 1925, the long-distance transmission of natural gas from the extensive reserves of the Southwest to the densely-populated and highly-industrialized North and East portions of the United States.

But the new fuel markets opened to the producers of natural gas by these long-line transporters are not alone responsible for the importance of the industry today. Technological advances in manufacturing processes, using natural gas and the liquids extracted therefrom as the basic raw material, have been remarkable, and the fields of application are virtually certain to expand in the future. As a result, natural gas is finding increased use also as a raw material in the manufacture of carbon black, chemicals, drugs, plastics and numerous other products. A tremendous potential market is afforded by the possible synthesis of gasoline and other liquid fuels from natural gas. Furthermore, gas in ever-increasing quantities is finding utilization in field operations for pressure maintenance, gas-lifting and secondary recovery.

RESERVES AND PRODUCTION

To this point, an attempt has been made to sketch briefly the many elements and factors which, to this time, have influenced the growth and development of the natural gas industry. It has been stated that the industry today is in a healthy and vigorous state, and is one of considerable importance. To substantiate a statement of this nature relative to an industry, any industry, the points of prime significance which first must be developed are two in number: Firstly, resources of supply of the basic raw materials; and secondly, existence and continuance of a sound demand for the product.

The raw material of the natural gas industry is the gas itself. The resources of supply of this basic commodity are represented, in the main, by the proved reserves of natural gas. There should be shown first, then, that the reserves of natural gas are of sufficient magnitude to support the past and anticipated growth of the industry.

Despite rapid gains in production and demand, estimates of natural gas reserves in the United States have increased steadily, almost year after year, to the all-time high of 180.4 trillion cu ft at the close of 1949 (Fig. 1). The net production of 6.2 trillion cu ft during 1949, an average of 17.1 billion cu ft per day, was much greater than in any previous year, yet proved reserves increased by 6.5 trillion cu ft. This reflects that the year's findings and revisions were more than twice the total volume produced. It is interesting to note that, on the basis of equivalent heat value, the known reserves of natural gas are potentially greater than are those of crude oil. Of comparable significance, it is estimated that the present proved reserves of natural gas should yield, from present

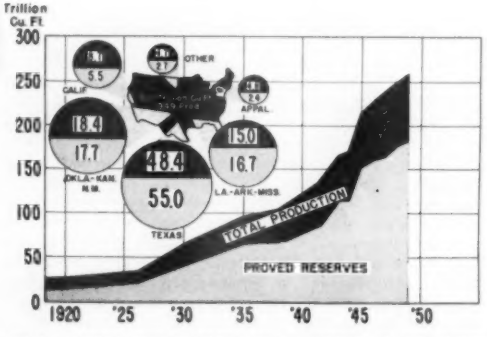

FIG. 1 — NATURAL GAS RESERVES AND PRODUCTION IN THE UNITED STATES.

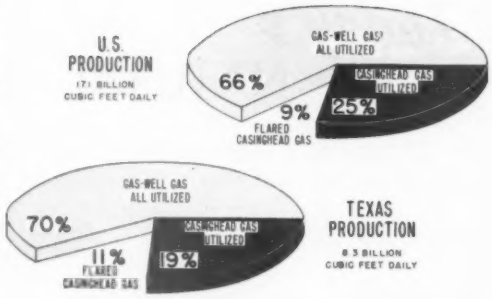

FIG. 2 — CASINGHEAD GAS LOSSES RELATIVE TO TOTAL GAS PRODUCTION IN 1949.

methods of extraction, a total of 3.73 billion bbl of liquid products. As a basis for comparison, this volume is approximately 16.4 per cent of the presently proved reserves of crude oil.

It is of further interest to note the geographic distribution of natural gas reserves and production. The seven-state area of Texas, Louisiana, Arkansas, Mississippi, Kansas, Oklahoma and New Mexico is credited with essentially 90 per cent of the total gas reserves for the United States. The State of Texas, alone, contributes 55.0 per cent (99.2 trillion cu ft) of the nation's total gas reserve, and during 1949 its production of natural gas amounted to 48.4 per cent of the total volume produced. And as a point for interesting contrast, consider this: In 1889, 60 years ago, federal statistics for the first time classified Texas as a gas and oil producing state, valuing its annual production of oil (48 bbl) and natural gas at $1,728.

Coincident with the production of natural gas, there was extracted and recovered during 1949 a total volume of 175.7 million bbl of liquid products, including an estimated 20.4 million bbl recovered by separation on the leases. This volume of liquid products recovered from natural gas, equivalent to nearly 482,000 B/D, approximates 9.7 per cent of the volume of crude oil produced in the United States during 1949.

CASINGHEAD GAS CONSERVATION

A discussion on the production of natural gas would be incomplete without reference to the remarkable accomplishments towards conservation of casinghead gas. The results of the splendid cooperation between the state regulatory bodies and the producers are becoming more and more evident. Tremendous strides in this direction already have been made, and the industry is relentlessly approaching the feasible ultimate in casinghead gas conservation.

The conservation problem concerns only casinghead gas, which constitutes about 30 per cent of the nation's present total reserves of natural gas. The other 70 per cent of the reserves is non-associated gas, which is produced only in response to market demand. Casinghead gas, by the nature of its occurrence and the conditions under which it is produced is not utilizable strictly on a demand basis.

Until a very few years ago, most of the casinghead gas produced in the oil fields of the Southwest was flared. The reason

for this was that the very limited market and the low prices offered for the gas were not sufficient to warrant the heavy investments and high costs involved in gathering the gas and rendering it marketable. Casinghead gas usually is produced in relatively small quantities and at low pressures, distributed over widely scattered and, often, isolated areas. After gathering, it usually must be compressed and processed, and often has to be treated to remove sulphur, water and other objectionable components. These economic considerations existed then as they do now, but somewhat improved prices and additional market outlets developed during recent years have improved the situation considerably. Even with recently improved prices, however, casinghead gas conservation projects still afford small financial return because such high investment and operating costs are incurred in effecting the utilization.

During 1949, the daily average production of natural gas in the United States was 17.1 billion cu ft (Fig. 2). Of this amount, an estimated 5.8 billion cu ft, or about 34 per cent, was casinghead gas. Nearly 74 per cent, or 4.3 billion cu ft per day, was utilized, and the remaining 1.5 billion cu ft per day was flared. Since all the gas-well gas produced was utilized, the overall gas utilization was 91 per cent.

In the same year, 1949, Texas produced 48.4 per cent of the nation's total production of natural gas, or a daily average of 8.3 billion cu ft. Of this total daily amount, an estimated 2.5 billion cu ft, or 30 per cent, was casinghead gas. It is estimated that 1.6 billion cu ft per day of this casinghead gas, or 64 per cent, was utilized, and the remainder, 0.9 billion cu ft per day, was flared. The overall gas utilization, including the non-associated gas, was approximately 89 per cent. This is a notable accomplishment, even though the overall utilization was less than the 91 per cent for the nation, when it is recognized that Texas in that year produced 40 per cent of the entire nation's output of crude oil.

INCREASING DEMANDS

It has been stated previously that the second requisite for a healthy industry is the existence and continuance of a sound demand for the product. In developing the picture of reserves, or resources of supply, which was the first requisite, attention was directed to production of natural gas. Production is integrated to a certain degree, and particularly as regards gas-well production, to the demand for natural gas. A more critical analysis of the demand situation, however, points up some interesting conditions.

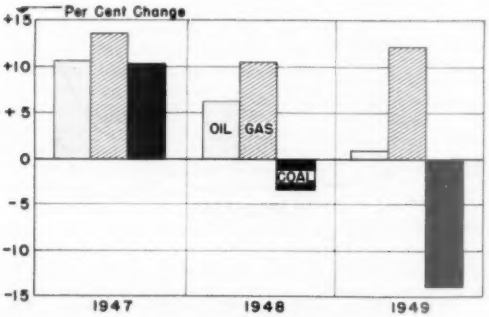

FIG. 3 — FUEL DEMAND TRENDS.

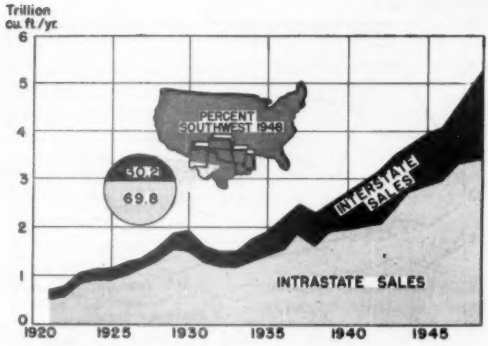

FIG. 4—INTERSTATE AND INTRASTATE SALES, MARKETED PRODUCTION.

Since the prime demand for natural gas is for utilization as a fuel, it is of interest to examine briefly its position today as an energy-source. The principal sources from which the United States derives its energy are coal, petroleum, natural gas and water power.

Water power contributed during 1949 only 4.8 per cent of the total energy consumed in the nation. Our prime interest, therefore, should be directed toward the mineral resources — coal, petroleum and natural gas. Since the early 1900's, substantially all of the enormous increase in energy consumption has been contributed by petroleum and natural gas. This trend has been particularly pronounced and significant during the last 20 years. Over this period, there has been more than a 35 per cent increase in mineral fuel consumed. This entire increase has been supplied by petroleum and natural gas, while coal today supplies less than in 1929. The marked increase in the use of natural gas is significant.

Oil and natural gas today supply about 60 per cent of the mineral fuel requirements of our country, while coal furnishes the remaining 40 per cent. In 1920, by contrast, coal supplied two-thirds of the mineral energy and oil and gas together supplied the remaining one-third. This condition has obtained in spite of the tremendously larger reserves of coal.

Two salient factors contribute to coal's loss in position — price and stability of supply. Strikes, and the constant threat of strikes, in the mining of coal have caused industry and the public in general to shift from coal to oil or natural gas, where possible, for their fuel requirements. In 1947, demand for all fuels was high (Fig. 3). In 1948, oil and gas continued to gain, but coal lost position considerably. During 1949, the demand for oil had leveled off, while gas continued to gain. By contrast, the demand for coal dropped sharply as the result of strikes and price increases.

The index of wholesale fuel prices reflects that, for many years, oil and gas have been much cheaper than coal. This is the most significant reason for the marked shift from coal to oil and natural gas during the past 20 years. Natural gas remains cheap today, and it is, by far, the most convenient, efficient and desirable fuel.

The relatively low price of natural gas has attracted millions of additional household customers. The number of residential users of natural gas in the United States is now approaching

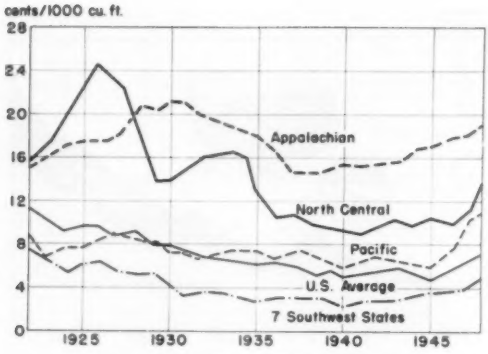

FIG. 5 — TRENDS IN WELLHEAD GAS PRICES.

12 million, whereas as late as 1938 it was only six million. Even though this vast number of domestic users represents more than 90 per cent of the total number of natural gas consumers, they purchase and use only 18 per cent of the total volume of natural gas marketed. The remaining 82 per cent of the marketed volume is sold for industrial and commercial purposes.

The construction and expansion of long-distance interstate transportation lines in recent years has attracted considerable attention. It is generally thought that the bulk of natural gas sales are made to these inter-state transporters. It may be surprising to know that in 1948, nearly 70 per cent of the marketed production of natural gas in the seven southwestern states, amounting to 2.8 trillion cu ft, was consumed in the state where produced; in other words, the gas was transported and sold in *intra*state commerce (Fig. 4). When field usage for pressure maintenance and cycling is included, the seven-state area consumed 75.9 per cent of its production. The segregation on nationwide sales reflects 65 per cent was used in the state where produced.

PRICE TRENDS

All that has been said previously regarding the natural gas industry, reverts to the producer as the very essence and foundation of the whole structure. Just what, then, is his position today, and how has he fared economically, on his gas production, in the tremendous expansion for which he primarily is responsible?

For the producer in the seven southwest states, which possess practically 90 per cent of the nation's reserves of natural gas, the answer is, "not very well." In 1948, this seven-state area accounted for 78 per cent of the nation's natural gas production, consumed 57 per cent and sold 21 per cent to remote markets in the North, East and West. And for that predominant part in production and sales the Southwest producer received an average price at the wellhead for his gas of 4.4 cents per Mcf (Fig. 5), considerably less than that received by producers in any other area, or the average received over the United States. Out of every dollar spent by the average householder in the North and East for gas produced originally in the Southwest, the average producer receives only about seven cents, while the other 93 cents goes to the transporter and the distributor of the gas.

Wellhead prices have improved somewhat in recent years, but even yet are far too low. Even at 10 cents per Mcf, it is comparable to buying fuel oil at 60 cents per bbl. Gas is being sold at the wellhead today, in many instances, at a unit cost less than the current cost of finding and developing gas reserves, much less the cost of producing, gathering, and making the gas marketable, which often requires expensive compression.

THREAT OF FEDERAL REGULATION

The foremost problem confronting the natural gas industry today, and a definite impediment to its continuing growth, is the growing threat of Federal regulation and control of the independent producers of gas. By "independent producers" is meant those producers, whether they be large companies, small companies or individuals, who are not affiliated in any way whatsoever with companies engaged in interstate transportation of natural gas for re-sale. Because this threat pretends to concern only a particular phase of a business, the general public is not adequately advised of the situation and the seriousness of its implications.

This threatening condition has grown out of the administration of natural gas in interstate commerce and the subsequent the intent of Congress by this Act to regulate the transportation of natural gas in interstate commerce and the subsequent sale of that gas to distributors for re-sale; and just as clearly the Act specifically exempted from its provisions the production and gathering of gas at one end, and its local distribution at the other. Competition among interstate transporters is limited by the nature of the business; hence, there was reason for imposing Federal regulation on this phase of gas operations. Again, local distribution of gas is a public utility function, and its regulation rightly was left to local regulatory bodies. With equal logic, Congress did not intend to impose Federal regulation on the highly competitive producer of natural gas. The administration of the Act was placed in the hands of the Federal Power Commission.

It was intended by Congress in the Natural Gas Act that the interstate transporter would purchase his gas in an open competitive market, and be allowed to re-sell the gas at a rate sufficient to cover the purchase price plus a reasonable return, say 6 or 6½ per cent, on his investment. In effect, the Federal Power Commission was empowered to set the rate which could be charged by the transporter for the service of transportation.

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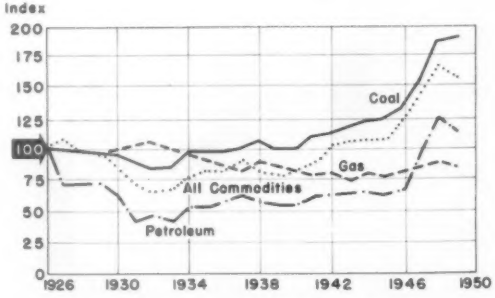

FIG. 6 — GAS COSTS IN 1950 COMPARED TO 1926.

Education for Research in Petroleum Engineering

By John A. Putnam
Assoc. Prof., Univ. of California, Member AIME

The Specialized Industry of Petroleum Production Requires Highly Educated Engineers. An Important Educator Outlines Here an Education for Research.

Introduction

There have developed in the field of petroleum engineering a number of functional specialties which, however, are no different from the specialties of other professional branches of engineering in that all are based on a common foundation of basic engineering science. These functional specialties represent the day-by-day applications or uses of scientific findings. The improvement toward greater efficiency in their applications and the development of better methods from new scientific discoveries are the economic justifications for research.

Before attempting to discuss the specific features of an education for research in petroleum engineering it seems desirable first to review briefly the trends in engineering education in general.

Trends in Engineering Education

World War II accentuated two salient features in regard to American engineering education: (1) the flow of basic scientific material from overseas all but ceased due to the ravages of the war and the unsettled conditions following in its wake, and (2) workers in the natural sciences undertook many engineering functions during and since the war. These two features, together with the demands of a highly competitive and complex industrial society, have had profound effects on the philosophy of engineering education in this country. One effect has been a general broadening of engineering curricula to include more basic subjects of a general education such as English, history and economics. Another effect, perhaps the most important one, has been the acceleration of a general movement to replace some of the highly practical courses of study, which emphasized technical methods of use and application, with courses which give far greater emphasis to the development of basic theory, to fundamental science, and to research. These curricula changes apply primarily to undergraduate programs. The general opinion among leading educators and industrialists as well as practicing engineers, is that a graduate who is well grounded in fundamentals finds it relatively easy to acquire the details of many special applications through self-study and reading during his apprenticeship; whereas, after graduation, it is extremely difficult for him to strengthen his understanding of fundamental engineering science and mathematics without special guidance and assistance. This observation appears to support the contention that specialization can be most effectively accomplished either by on-the-job apprenticeship or by graduated study or a combination of both, provided the student has been well indoctrinated in fundamentals during his period of undergraduate study.

The general emphasis on basic fundamentals in all engineering education is even more important in the graduate program. Equally important, however, is the development of an engineering viewpoint in the productive research man or special design engineer. He must realize that his activities must be governed by economic factors and be able to compromise under limitations imposed by available materials and the important factor of timing. Herein lies the principal difference in training for advanced technical service and training for research in natural science.

Although engineers study science and some engage in research in the engineering sciences, they differ fundamentally from scientists in that the latter are concerned with principles, and solutions of problems in principle are satisfactory to them. On the other hand, the engineers have failed unless they achieve solutions in practice.

Research Requires Teamwork

Present day research problems are usually so complex that teams of experts are required to resolve them. A glance at the organization chart of the research division of a typical oil company, for example, reveals an administrative framework interlaced with groups of scientific and technological experts.

This network represents a complex team organized to solve many problems and to develop improved technological applications which are vital to the company's survival in the highly competitive conditions of modern industry. Within this vast activity are smaller groups of specialists working on individual problems. Even the efforts of a single individual, assigned to one facet of a larger problem, often require the advice of other specialists. Engineers with broad undergraduate training and specialized graduate study in the engineering sciences, who also possess by reason of experience the engineering viewpoint regarding economic factors and useful results, should make ideal leaders of such research teams.

The concept of teamwork in research has a direct bearing on the education problem. Teamwork connotes a high degree of specialized training which, at first glance, is contrary to the philosophy of a broad grounding in fundamentals discussed earlier. However, it was pointed out that recent trends call for specialization either by on-the-job training or by graduate study. At present the master's degree marks the level most generally reached in graduate study. Although any advanced degree denotes specialization, the master of science degree may indicate specialization in the application and design phases of a recognized professional field of engineering such as communications, petroleum production or heat power. On the other hand, it may indicate specialization in advanced phases of such basic engineering sciences as thermodynamics, fluid mechanics, elastic theory or mechanics of materials.

Both types of graduate study are needed but the latter is of primary importance in view of modern indus-

(Continued on Page 7, Section 2)

PRELIMINARY
Oklahoma City Fall Meeting Program

The Following Program for the Mid-Continent Fall Meeting is Tentative. All Papers are Subject to Change or Withdrawal.

Thirty-three papers on the various phases of production, drilling and natural gas have been tentatively committed and accepted for presentation at the 1951 Mid-Continent Fall Meeting of the Petroleum Branch, AIME, to be held Oct. 3-5 in Oklahoma City's Biltmore Hotel.

The program, although still subject to change, was arranged by the Technology Committee at a meeting in Dallas June 29. Most sessions will be held in the Biltmore's Civic Room with concurrent sessions to be held in the Sky Room of the Oklahoma Club, located one-half block west of the Biltmore.

In addition to the 33 papers already planned, four papers on economic aspects of the industry will also be given. An open meeting of the Branch Executive Committee will round out the formal program.

Chairman of the 1950 Technology Committee is Earl Kipp of The California Co. Vice-chairmen are Jack H. Abernathy of the Big Chief Drilling Co., Drilling Technology; Henry L. Waszkowski of Magnolia Petroleum Co., Production Technology; and E. G. Trostel of DeGolyer and MacNaughton, Natural Gas Technology. Hosts for the meeting will be members of the Oklahoma City Section. Officers of the various committees are H. L. Waszkowski, Finance and Entertainment; A. E. Sweeney, Publicity; W. M. Edinger, Registration; J. C. Cordell, Hotel Arrangements; L. F. Elkins, Meeting Arrangements; and D. A. McGee, General Arrangements. Mrs. L. F. Elkins will be chairman of the Ladies Activities Committee.

The tentative schedule of papers and authors follows:

WEDNESDAY, OCTOBER 3

9:30 - 11:45 a.m. — Field Case Histories

"Results of Gas Injection in the Cedar Lake Field," by E. D. Whitis, J. E. Huzarevich and R. M. Leibrock, Stanolind Oil and Gas Co.

"Poza Rica, Its Development, Exploitation and Near Future," by J. Colmo, A. Barnetche and J. Hefferan, Petroleos Mexicanos.

"Electric Analyser Study of Woodbine Basin," by H. E. Stamm III, R. C. Rumble and H. H. Spain, Humble Oil and Refining Co.

9:30 - 11:45 a.m. — Reservoir Engineering

"Effect of Data Errors on Typical Reservoir Calculations," by C. A. Hutchinson, Jr., Atlantic Refining Co.

"A Simplified Method for Computing Oil Recovery by Gas or Water Drive," by Henry J. Welge, The Carter Oil Co.

"Displacement Mechanism in Multi-Well Systems," by Loyd R. Kern, Atlantic Refining Co.

2:00 - 5:00 p.m. — Production Operations

"The Delta-Log, A Differential Temperature Surveying Method," by Raymond B. Basham and C. W. Macune, Westronics, Inc.

"Strata Flow Processes — A New Method for Determining the Water Entry Point in Producing Wells," by Wilfred Tapper, Halliburton Oil Well Cementing Co.

"Hydrafrac Operations in the Spraberry Production, West Texas," by Waldo L. Grossman, Halliburton Oil Well Cementing Co.

THURSDAY, OCTOBER 4

8:30 - 11:30 a.m. — Drilling Technology

"Light Weight Cement and Anti-Loss Circulation Materials and Methods," by Don Hall, Great Lakes Carbon Corp.

"The Guard Electrode Logging System," by John E. Owen, Geophysical Research Corp., and Walton J. Greer, Halliburton Oil Well Cementing Co.

"Radial Filtration of Drilling Muds," by C. L. Prokop and H. W. Brown, Humble Oil and Refining Co.

"The Effect of Circulating Media and Nozzle Design on Rock Bit Performance," by Lyle L. Payne, Hughes Tool Co.

8:30 - 11:30 a.m. — Water Flooding

"A Method for Predicting the Tendency of Oil Field Waters to Deposit Calcium Sulfate," by Henry A. Stiff, Jr., and Lawrence E. Davis, Atlantic Refining Co.

"Behavior of Dissolved Oxygen in Brine," by D. C. Bond, G. A. Marsh and G. G. Bernard, The Pure Oil Co.

"Mobility Ratio — Its Influence on Flood Patterns During Water Encroachment," by J. S. Aronofsky, Magnolia Petroleum Co.

"Some Conclusions from Profiling Water Input Wells," by H. H. Kaveler and Z. Z. Hunter, Phillips Petroleum Co.

1:30 - 4:30 p.m. — Reservoir Engineering

"The Use of Scaled Models in Reservoir Engineering Studies" by Walter Rose, Texas Petroleum Research Committee.

"Visual Examinations of Fluid Behavior in Porous Media — Part I," by Alfred Chatenever, University of Oklahoma, and John C. Calhoun, Pennsylvania State College.

"The Effect of Withdrawal Rate on the Uniformity of Edgewater Intrusion," by Morris Muskat, Gulf Oil Corp.

"Possibility of Cycling Deep Depleted Oil Reservoirs After Compression to a Single Phase," by Donald L. Katz, University of Michigan.

FRIDAY, OCTOBER 5

9:00 - 12:00 m. — Drilling and Well Completion

"A New Additive for Control of Drilling Mud Filtration," by R. A. Salathiel, Humble Oil and Refining Co.

"Experimental Evaluation of Well Perforation Methods as Applied to Hard Limestone," by Henry Lewelling, Atlantic Refining Co.

"Correlation of Radioactive Logs of the Lansing and Kansas City Groups in Central Kansas," by J. V. Morgan, Stanolind Oil and Gas Co.

"Lost Circulations Problems — Application of Time-Setting Clay Coments," by J. V. Messenger and J. S. McNiel.

8:30 - 12:00 m. — Gas Technology

"The Calculation of Pressure Droup in the Flow of Natural Gas Through Pipe," by Fred H. Poettmann, Phillips Petroleum Co.

"Efficiency of Gas Displacement from Porous Media by Liquid Flooding," by T. M. Geffen, D. R. Parrish, G. W. Haynes and R. A. Morse, Stanolind Oil and Gas Co.

"Natural Gas in the Province of Alberta, Canada," by J. F. Dougherty, Empire Trust Co., Anthony Folger and Joffre Meyer, DeGolyer and MacNaughton.

"Equilibrium Vaporization Ratios for Nitrogen, Carbon Dioxide, Hydrogen Sulfide and Methane in Crude Oil - Natural Gas and Absorber Oil - Natural Gas Systems," by R. H. Jacoby and M. J. Rzasa, Stanolind Oil and Gas Co.

1:00 - 4:00 p.m. — Production Research

"Method for Determining Wettability of Reservoir Rocks," by R. L. Slobod and H. A. Blum, Atlantic Refining Co.

"Analysis of the Evaporation Method for Determining Interstitial Water," by Charles G. Dodd, U. S. Bureau of Mines.

"Use of Digital Electronic Computer in Calculations of Dissolved Gas Drive," by H. H. Rachford, Jr., and C. E. Williams, Jr., Humble Oil and Refining Co.

"Prediction of Saturation Pressures for Condensate Gas and Volatile Oil Mixtures," by E. I. Organick and B. H. Golding, United Gas Corp.

PRELIMINARY
Los Angeles Fall Meeting Program

Papers to Be Presented at the West Coast Fall Meeting are Now Being Written. All are Subject to Change or Withdrawal.

A tentative schedule of papers for the West Coast Fall Meeting of the Petroleum Branch, AIME, has been released by Wayne Glenn, vice-chairman for California of the Technology Committee. All papers at this early date are subject to withdrawal.

The West Coast Fall Meeting will be held again this year in the Elks Club Oct. 25, 26, in Los Angeles. General Chairman for the meeting is C. P. Watson. Other officers are Glenn, program chairman; Kemp E. Barley, exhibit chairman; K. B. McNamara, dinner dance chairman; and M. E. Loy, luncheon chairman.

The tentative program of papers follows:

THURSDAY, OCTOBER 25

Morning Session

"Analog Productivity Relationships Applied to Current Gun Perforating," by Val L. Forsyth, Lane-Wells Co.

"Improved Multiple Phase Flow Studies Employing Radioactive Tracer," by V. A. Josendal, B. B. Sandiford and J. W. Wilson, Union Oil Co.

"Effect of Drilling Fluids on Productivity," by Charles C. Wright, Oilwell Research, Inc.

"High Pressure-High Temperature Filtration Behavior of Drilling Fluids," by F. W. Shremp and V. L. Johnson, California Research Corp.

Afternoon Session

"California Gas Supply, Present and Future," by S. A. Bradfield, Southern California Gas Co.

"Utilization of Production Research," by J. E. Sherborne, Union Oil Co.

"Economic Evaluation of Gas Injection," author unassigned.

"Cook Ranch Gas Injection — A Phenomenal Success," by W. W. Wilson, Continental Oil Co.

FRIDAY, OCTOBER 26

Morning Session

"High Viscosity Oils, Effect on Oil Recovery," by Martin Felsenthal, Continental Oil Co., and S. T. Yuster, University of California.

"Recent Laboratory Investigations in Secondary Recovery in California," by Norris Johnston, Petroleum Technologists, Inc.

"Water Flood Case Histories," by E. P. Burchaell, Honolulu Oil Corp., and E. R. Smith, Seaboard Oil Co.

Afternoon Session

"Taxes — Our Biggest Expense," author unassigned.

"North Coles Levee Pressure Maintenance," by C. A. Davis, Richfield Oil Corp.

"Technical Advancement in Modern Drilling," by A. H. Bell, Bell and Burden, Inc., (Joint paper by members of American Association of Oilwell Drilling Contractors).

Petroleum Conservation Volume To Be Published

A new volume entitled *Petroleum Conservation*, edited by Stuart E. Buckley of Humble Oil and Refining Co., will be published by the Institute through the Petroleum Branch office in late September or early October. Publication of the volume is sponsored by the Henry L. Doherty Memorial Fund, and it will be designated as a Doherty Memorial Volume.

Many members of the Branch have looked forward to publication of the volume, and it is expected to have an excellent reception in the Branch and in the petroleum industry in general. The plan for writing the manuscript has been for a number of contributors to submit material to Stuart E. Buckley, the editor, and he has woven the contributions and original material into a cohesive manuscript. The volume will be in six by nine in. size, printed in a very readable type on soft paper, and bound in the standard AIME red cover. It will contain approximately 300 pages.

An exception to the standard discount of 30 per cent to AIME members on Institute volumes has been made in this case. The price of the volume to AIME members will be only $3.00 — one-half of the retail price of $6.00. This exception was made in order to make the volume available to members approximately at cost. An order form with a business reply card will be mailed to all Petroleum Branch members in the immediate future, and members may easily purchase the volume with this card.

Contributors to the volume are: Stewart P. Coleman, with assistance of E. S. Neal and E. F. Sibbern; Parke A. Dickey; A. F. van Everdingen; K. C. Heald; Francis E. Heath; John R. Haley; H. H. Kaveler; C. V. Millikan; G. G. Oberfell, with assistance of R. C. Alden and T. W. Legatski; Eugene A. Stephenson and W. V. Vietti. Editor Buckley also worked with an Editorial Advisory Committee which consisted of C. E. Beecher, E. DeGolyer, Robert E. Hardwicke, Hallan N. Marsh, C. V. Millikan, A. C. Rubel and W. V. Vietti.

The volume will contain ten chapters, with chapter titles as follows:

I — Elements of Conservation
II — Petroleum Resources
III — The Petroleum Reservoir
IV — Characteristics of Reservoir Fluids
V — Fundamentals of Oil Recovery
VI — Efficient Operation of Petroleum Reservoirs
VII — Secondary Recovery
VIII — Pressure Maintenance
IX — Conservation and State Regulation
X — Cooperative Development and Unit Operation

Although the volume is written in non-technical language, it will be a valuable addition to the library of every petroleum engineer. Chapters III, IV and V especially contain information that will add to the industry's knowledge of reservoir behavior. Two leaders of the Petroleum Branch have expressed their viewpoints on the book as follows:

HAROLD DECKER — "*Petroleum Conservation* is an outstanding contribution to the oil industry and is a valuable volume for libraries of companies, industry executives, engineers, attorneys and others interested in the vital and increasingly important subject of conservation of our petroleum resources."

LLOYD E. ELKINS — "This volume very effectively brings into focus the status of conservation developments in the oil industry up to this time. Its use by executives, engineers, geologists, lawyers and royalty owners interested in the welfare of the oil industry should result in solidifying a foundation upon which continued and even accelerated progress can be made in the future." ★ ★ ★

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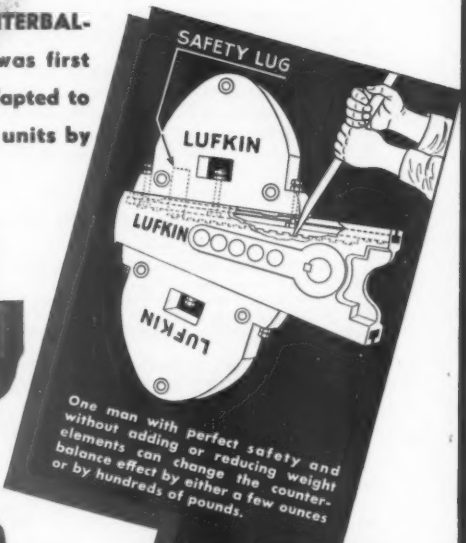

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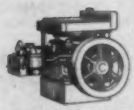

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Technical Note 85——

A HIGH TEMPERATURE GAUGE GLASS FOR THE VISUAL OBSERVATION OF CRITICAL PHENOMENA

JOHN R. SPENCER,* TEXAS PETROLEUM RESEARCH COMMITTEE, AUSTIN, TEX., MEMBER AIME

ABSTRACT

A capillary tube variable volume cell is described, which has operated satisfactorily over a range of 100°F and 3,500 psi to 550°F and 1,500 psi. The cell contents are entirely visible over the length of the capillary with the exception of a space at the top amounting to three per cent of the total volume. Observations on the critical behavior of simple systems have been greatly facilitated by the apparatus, it being possible to establish the critical conditions for a particular mixture in the course of a day's run.

INTRODUCTION

Many types of apparatus have been designed for obtaining data on the phase relationships of hydrocarbon systems. Such apparatus can in general be subdivided into two classifications; (1), indirect measurement of phase volume, and (2), direct visual observation of phase volume, each of which has outstanding advantages and disadvantages.

Indirect measurement of phase volume requires the use of rather elaborate apparatus including internal probes in which are located the device for determining the locus of the interface between phases. Such equipment is by its very nature costly, and is complex from the standpoint of operating technique. Probing techniques can be used, however, over wide ranges of temperature and pressure with a high degree of reproducibility.

Apparatus for visual observation of phase behavior obviously has the advantage of enabling the experimenter to see exactly what takes place, but because the material to be tested is contained in a cell constructed of both metal and glass, is limited severely as to the temperature range of operation. Furthermore, the maximum pressure usually is limited by the choice of material used for sealing the glass to the metal, and by the strength of the glass itself. In the interest of increased efficiency of observation, as much of the cell as possible should be visible to the eye. Glass capillary tubes have been used successfully but have always given difficulty at the metal-to-glass seal. An apparatus has been devised to overcome the problems of sealing and resistance to temperature effects that have heretofore been the limiting factor with glass apparatus in the observation of phase volumes at elevated temperature and pressure.

*Now with the Continental Oil Co., Ponca City, Okla. This Note is Contribution No. 13, Texas Petroleum Research Committee, G. H. Fancher, Director.

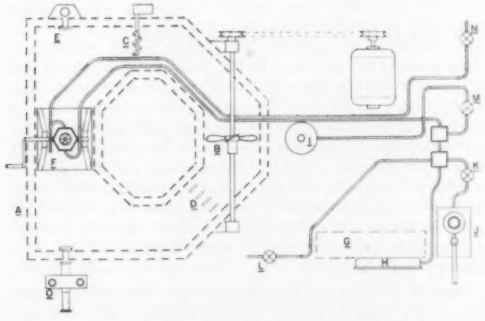

FIG. 1 — GENERAL LAYOUT OF THE APPARATUS.

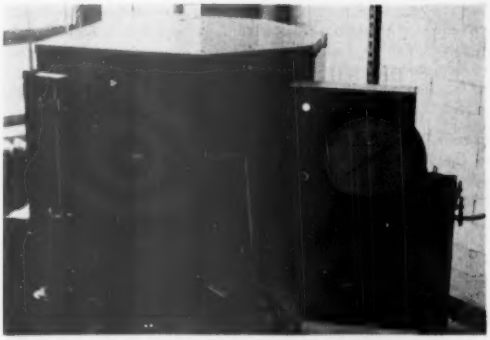

FIG. 2 — PHOTOGRAPH OF THE ASSEMBLED UNIT.

APPARATUS

The objective which dictated the general arrangement of the apparatus (Figs. 1 and 2) was simplicity of operation. The air bath, *A*, was constructed of an iron framework to which was attached approximately one inch of glass wool bats which were covered on the outside with "Masonite." A roughly

octagonal center piece was installed to provide forced circulation of the air by the fan, *B*, past the heaters, *D*, cell, *F*, and thermoregulator, *C*, respectively. The entire top of the box is removable to facilitate charging of the cell and to permit easy maintenance. Two windows are provided before and behind the cell to allow the operator to observe the contents against the background fluorescent light, *E*. The heaters, lights, and fan motor are all controlled from the switchboard, *G*.

Mercury is added to the cell from the pump, *J*, and the mercury shut-off valve, *K*, and is removed through the bleeder valve, *L*. Charging is carried out through the valve, *N*, and if the pressure of the gas sample is insufficient the cylinder, *I*, can be connected to allow compression of gas and its subsequent transfer to the cell. The 5,000 psi Heise bourdon tube gauge, *H*, always is connected to the mercury supply during operation. Liquid levels are observed with the screw type microcathetometer, *O*, which can be read consistently to within .002 in.

DETAILS OF CONSTRUCTION

Heat is supplied to the air bath by the four 500-watt heaters, *D*, one of which is connected through a mercury relay to the bimetallic thermoregulator, *C*. Considerable care was taken in designing the heaters to provide for as little restriction to the flow of air as possible. The heaters were constructed of pieces of one-quarter in. transite about two in. wide and 18 in. long, wound with 20-gauge nichrome ribbon. These were mounted in a frame and installed parallel to the air stream directly in front of the fan. The entire heater assembly can be removed as a unit by disconnecting the leads.

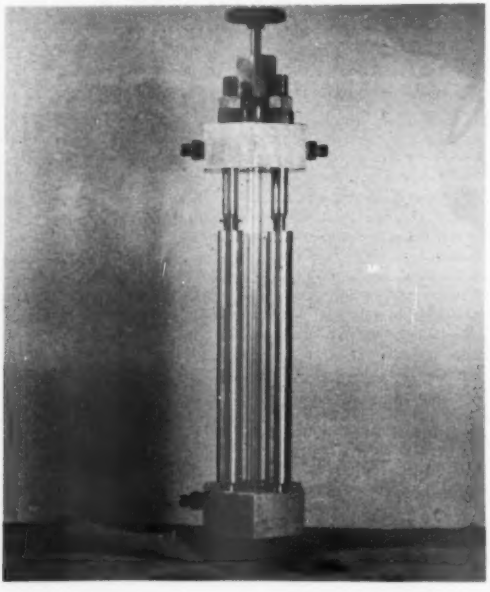

FIG. 3 — PHOTOGRAPH OF THE CAPILLARY CELL ASSEMBLED.

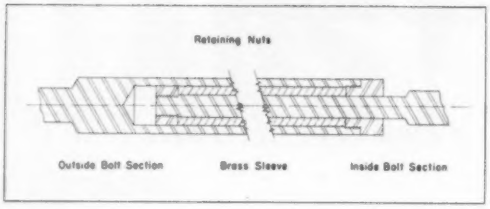

FIG. 4 — CROSS SECTION OF THE THERMALLY COMPENSATED TIE BOLTS.

Circulation of air is induced by the 10-in. fan, *B*, mounted on a three-quarter in. cold rolled steel shaft which turns between two bearings, both on the outside of the bath. The distance between the bearings, about 30 in., made imperative the use of a heavy shaft to eliminate any tendency of the assembly to "whip." Sleeve bearings were used on both ends of the shaft to keep it in alignment even though the initial assembly of the unit was made somewhat difficult.

Located in the air stream out of direct line of vision from the heaters, the cell receives only that heat supplied by contact with the air, and thus local overheating is prevented that might result from direct radiation from the heaters. The cell is mounted in trunions so that it is free to rotate through an angle of approximately 120° to permit agitation of the cell contents. Connections to the upper and lower ends of the cell are made through coils of one-eighth in. stainless steel tubing.

The appearance of the cell is similar to that of the usual tubular gauge glass used in industrial applications. Certain structural changes have been made, however, that greatly improve the performance characteristics (Fig. 3). The valves on the two ends of the cell are identical and are what is commonly called a "T" type valve, the stem being used to shut off the leg of the "T." These valves were used to allow the seat to be placed near the lower part of the valve, to reduce the volume of that part of the cell which can not be seen. The "T" type valve also facilitates bleeding and cleaning operations. A circular recess is cut in the lower side of the valves to accommodate the flat gaskets which were used. These gaskets are cut from Teflon sheet, 0.035 in. thick, and appear to be stable at temperatures well above those contemplated for the apparatus. The visual portion of the cell is a Pyrex capillary tube about two-and-one-half millimeters ID and about nine millimeters OD. In addition to squaring the ends of the tube by grinding, fire-polishing was found to be necessary if the tube was not to split lengthwise when pressure was applied. In assembly four bolts passing through the outer portion of the valves hold the valves against the ends of the glass tube, the Teflon gaskets providing the seal required.

These bolts must be compensated for thermal expansion because any relative change in length between the bolts and the tube assuredly would cause failure of the seals. An attempt

was made to find materials for the bolts that would have the same coefficient of thermal expansion as glass; and none were found. A very simple method was devised whereby any desired coefficient of expansion within limits could be built into the bolts (Fig. 4). This bolt is believed to have many applications other than the one described.

The bolt consists of three distinct parts; (1) the outer barrel, (2) the correcting sleeve, and (3) the inner rod. Any two metals having different thermal expansion characteristics can be used in its construction. Appropriate materials for the job at hand were cold rolled steel for the portions of the bolt under tension and brass for the correcting sleeve which is under compression when in use.

In order to establish the length of brass sleeve required for the proper thermal compensation, quantities are defined as follows:

l_g = length of the glass tube.
l_h = thickness of one valve between the gasket seat and the tie-bolt nuts.
l_s = length of the bolts as measured between the nuts on the outside of the valves.
l_B = length of brass sleeve required.
α_g = average coefficient of linear thermal expansion for glass over the temperature range desired.
α_s = average coefficient of linear thermal expansion for steel over the temperature range desired.
α_B = average coefficient of linear thermal expansion for brass over the temperature range desired.
Δt = temperature change.

Inasmuch as the relative positions of the parts making up the gauge assembly should remain unchanged, a length of brass sleeve must be used that will allow the bolts to expand by an amount equal to that of the glass plus that of the valve bodies.

The expansion of the bolt will be equal to

$$(\alpha_s l_s - \alpha_B l_B)\Delta t \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

that of the end blocks to

$$2\alpha_s l_h \Delta t \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

and that of the glass to

$$\alpha_g l_g \Delta t \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

Consequently,

$$(\alpha_s l_s - \alpha_B l_B)\Delta t = (\alpha_g l_g + 2\alpha_s l_h)\Delta t \quad . \quad (4)$$

and

$$\frac{\alpha_s(l_s - 2\ l_h) - \alpha_g l_g = l_B}{\alpha_B} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

If the valves and the bolt bodies were constructed from two different materials, Equation (5) could be modified appropriately, the principles employed being the same as those utilized in the derivation of Equation (5).

SUMMARY

This apparatus had been in use for approximately six months at the time this note was prepared (April, 1951), and the data obtained in its use have been satisfactory. One disadvantage is the small amount of sample available for subsequent analysis; however, this difficulty can be overcome by charging mixtures of known composition to the cell or by analyzing the contents of the cell by methods which do not require a large volume of material, as for example, the spectrophotometric method.

ACKNOWLEDGMENT

The author is indebted to W. A. Fickert, of the University of Texas, for the accompanying drawings. ★ ★ ★

Technical Note 83——

THEORETICAL NOTE ON LINEAR ABSORPTION METHODS OF DETERMINATION OF FLUID SATURATION IN POROUS MEDIA

LEONARD B. LIPSON, MAGNOLIA PETROLEUM CO., DALLAS, TEX., JUNIOR MEMBER AIME

Boyer, Morgan and Muskat,[1] with improvements by Morgan, McDowell, and Doty,[2] and Laird and Putnam,[3] have described a scheme for the determination of fluid saturation in porous media by measuring the x-ray linear absorbing power of particular fluids in the media. This method is one of several which depend on the linear absorbing power of the fluids in the porous medium. Other examples of linear absorption methods involve measurement of dielectric constant, gamma ray absorption, and ultrasonic attenuation. It is the purpose of this note to demonstrate by theortical considerations that the absorption versus saturation curve for a linear absorption method is not necessarily a single valued function of the saturation. Such non-unique behavior must be considered and evaluated before suitable saturation determinations can be made by a linear absorption method.

To illustrate the discussion, examples will be given only for the simplest cases of combinations of two different dielectrics. The dielectric constant method was chosen for illustration because it was thought to demonstrate most graphically the point in question.

According to Argue and Maass,[4] the resultant dielectric constant of a combination of two different dielectrics depends

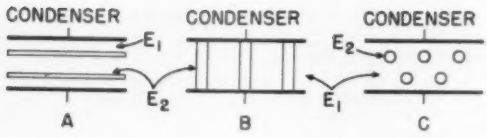

FIG. 1

on the orientation of the dielectrics in the electric field of the test condenser used to measure the dielectric constant. One case involves alternate slabs of dielectrics E_1 and E_2, perpendicular to the electric field of the test condenser, as shown in Fig. 1A. For this case:

$$1/E_m = A/E_1 + B/E_2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where E_m is the dielectric constant of the combination, A is the ratio of the path length through dielectric E_1 to the distance between the plates of the condenser (assuming the dielectrics have the same cross sectional area as the condenser), and B is the ratio of the path length through dielectric E_2 to the distance between the plates of the condenser.

It will be noted that the constants A and B are numerically equal to the fractional "saturation" of the region between the test plates of the condenser by the two dielectrics E_1 and E_2, respectively.

Another case involves alternate columns of the two dielectrics parallel to the electric field and forming a continuous path between the condenser plates, as shown in Fig. 1B. For this case:

$$E_m = AE_1 + BE_2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where E_m is the dielectric constant of the combination, A is the ratio of the cross sectional area of dielectric E_1 to the cross sectional area of the condenser plates (assuming the lengths of the dielectrics equal the distance between the condenser plates) and B is the ratio of the cross sectional area of dielectric E_2 to the cross sectional area of the condenser plates. As before the constants A and B are the effective "saturation" of the condenser by the two dielectrics.

Still another case is described by Lichtenecker[5] where dielectric E_2 is shown in the form of small particles distributed at random in dielectric E_1. This is shown in Fig. 1C. For this case:

$$\log E_m = A \log E_1 + B \log E_2 \quad . \quad . \quad . \quad . \quad . \quad (3)$$

where E_m is the dielectric constant of the combination, A is the ratio of the volume of dielectric E_1 to the volume of the condenser, *i.e.*, the effective "saturation" of the condenser by dielectric E_1. B is the ratio of the volume of dielectric E_2 to the volume of the condenser, *i.e.*, "saturation" of dielectric E_2.

Equations (1), (2) and (3) are plotted in Fig. 2 for $E_1 = 2.5$ (oil) and $E_2 = 80$ (water).

Equations (1) and (2) may be thought of as representing the limiting cases of the configuration of two fluids which might be expected to exist in a porous medium. Equation (3), or one similar in form, may be thought of as describing a fluid distribution more nearly representative of what might be expected actually to exist in a porous medium.

It could be concluded from Fig. 2 that any system of determination of fluid saturation in porous media using linear absorption methods would yield a non-linear calibration curve. This calibration curve would be different for different porous media and for different methods of obtaining a given saturation in the same medium. Therefore, the absorption vs. saturation curve, for a porous medium having both a drainage and an imbibition saturation history, should exhibit the same hysteretic effect[6] shown by the capillary pressure vs. saturation curve for that same medium.

ACKNOWLEDGMENT

Acknowledgment is made to the management of Magnolia Petroleum Co. for permission to publish this note.

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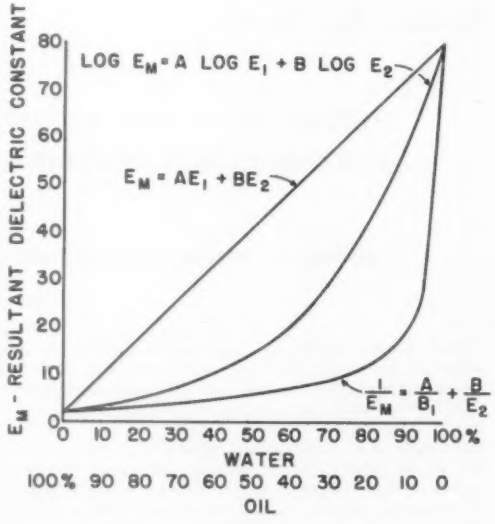

FIG. 2

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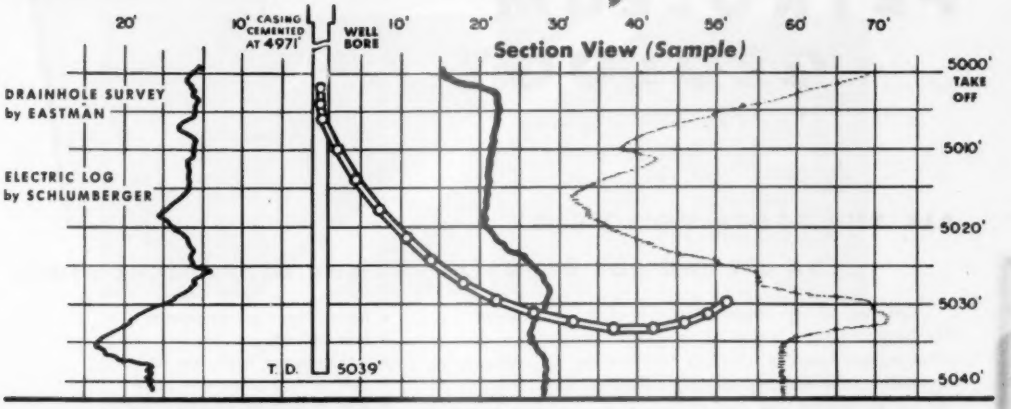

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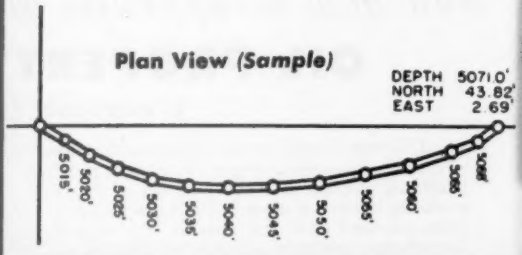

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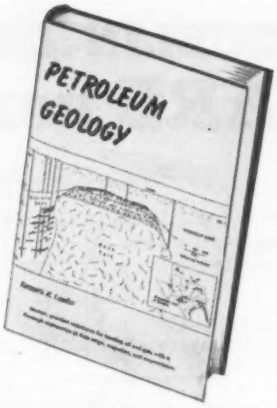

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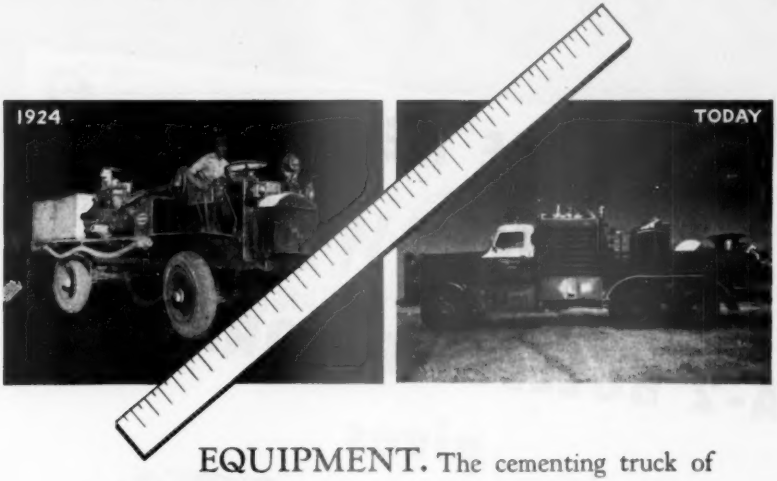

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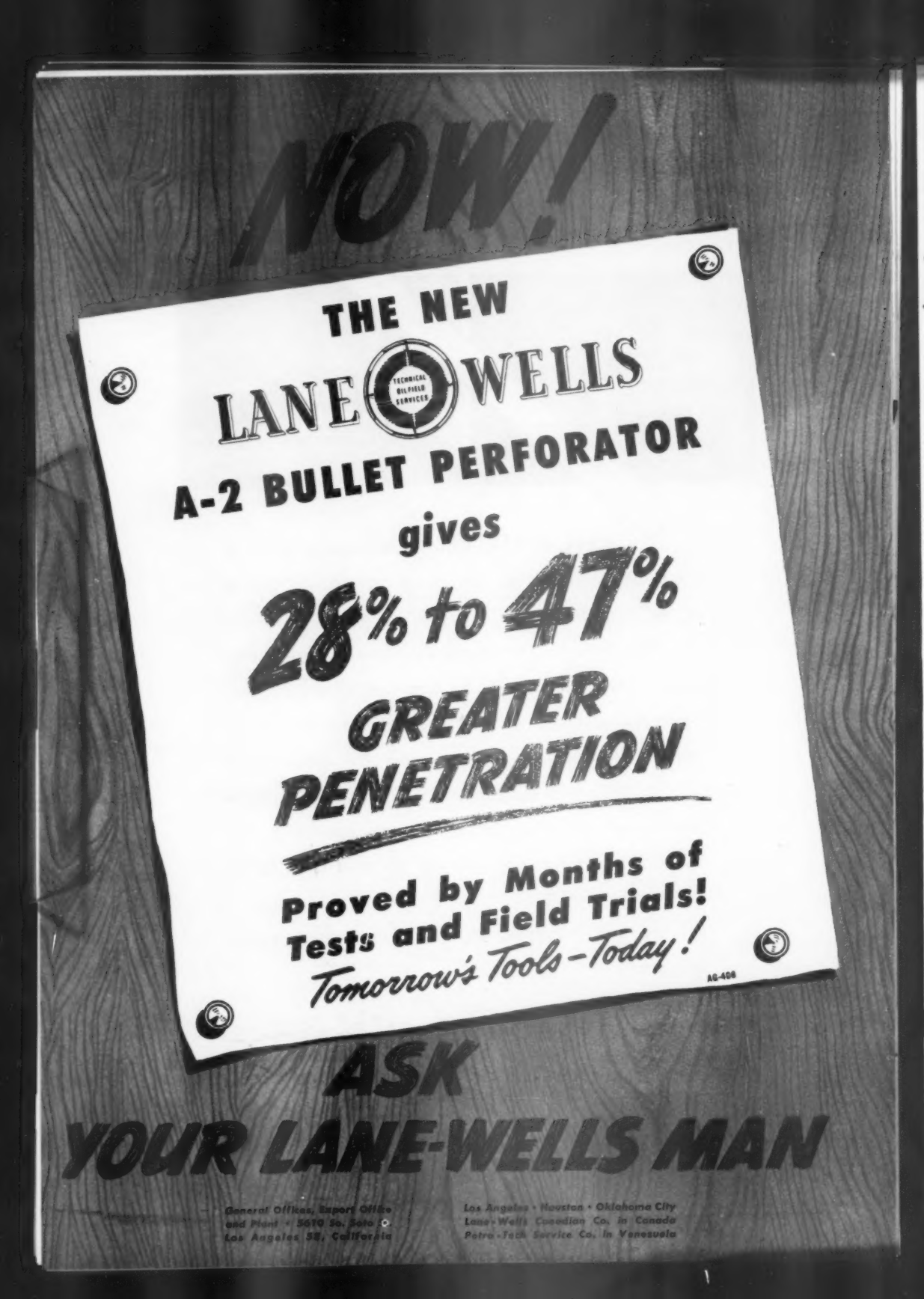
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PHASE EQUILIBRIA IN HYDROCARBON-WATER SYSTEMS

III—The Solubility of Methane in Water at Pressures to 10,000 PSIA

O. L. CULBERSON, GULF RESEARCH AND DEVELOPMENT CORP., HARMARVILLE, PA., AND **J. J. McKETTA, JR.,** MEMBER AIME, DEPARTMENT OF CHEMICAL ENGINEERING, THE UNIVERSITY OF TEXAS, AUSTIN, TEX.

ABSTRACT

Experimental and smoothed data are presented for the solubility of methane in water for temperatures of 77, 100, 160, 220, 280, and 340°F at pressures to 10,000 psia.

The minimum solubility phenomenon exists within this temperature range to pressures of 10,000 psia.

INTRODUCTION

The study of hydrocarbon-water systems has been extended to the determination of the solubility of methane in water at pressures to 10,000 psia. The experimental apparatus, and the technique, are the same as that previously reported.[1,2]

In the determination of the solubility of methane in water, only two phases were present at temperatures between 100 and 340°F, these being the vapor phase and the water-rich liquid phase. The determinations involved the agitation of methane and water in an equilibrium cell, withdrawal of a sample from the liquid phase, and the analysis of the sample. The experimental values determined in this manner are presented in Table I and in Fig. 1.

Since experimental and analytical techniques have improved since the initial experiments with this equipment, it was decided to repeat the 77°F isotherm determinations.[2] Fig. 1 shows that the individual results for this isotherm are much

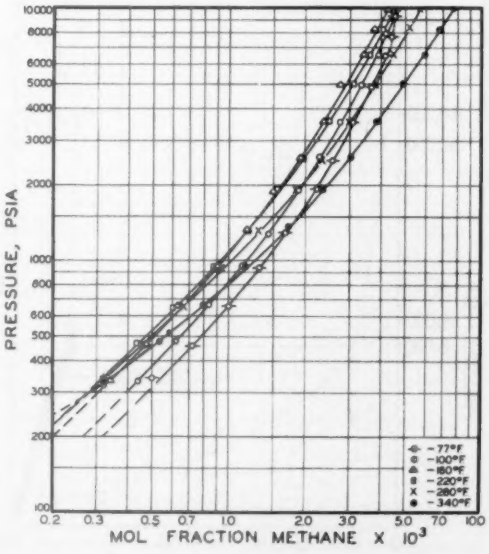

FIG. 1 — SOLUBILITY OF METHANE IN WATER AT CONSTANT TEMPERATURE.

[1]References given at end of paper.
Manuscript received in the office of the Petroleum Branch Nov. 16, 1950.

Table I — Experimental Values for the Solubility of Methane in Water
Pressure: Lb/Sq In. Abs (psia) Solubility: Mol Fraction CH_4

77°F		100°F		160°F		220°F		280°F		340°F	
psia	*MF* CH_4	psia	*MF* CH_4	psia	*MF* CH_4	psia	*MF* CH_4	psia	*MF* CH_4	psia	*MF* CH_4
341	0.000497	330	0.000440	331	0.000340	333	0.000323	336	0.000326	323	0.000323
459	0.000717	477	0.000619	467	0.000470	466	0.000432	464	0.000460	475	0.000535
659	0.001000	664	0.000839	659	0.000632	468	0.000472	654	0.000673	662	0.000789
934	0.001317	950	0.001123	943	0.000909	652	0.000611	941	0.000938	949	0.001150
1290	0.001678	1270	0.001440	1320	0.001183	945	0.000886	1310	0.001326	1360	0.001725
1930	0.002235	1900	0.001890	1880	0.001500	1310	0.001188	1900	0.001857	1920	0.002355
2495	0.002585	2575	0.002290	2555	0.001924	1900	0.001560	2480	0.002346	2580	0.003025
3515	0.003110	3535	0.002760	3535	0.002385	2535	0.001980	3555	0.003015	3580	0.003835
4810	0.003660	4910	0.003330	4925	0.002770	3570	0.002510	4975	0.003805	5045	0.004875
6440	0.004170	6525	0.00391	6525	0.00342	4965	0.00314	6525	0.00449	6525	0.00595
7795	(0.004370)	7870	0.00417	8220	0.00375	6525	0.00361	8270	0.00518	8210	0.00680
9300	(0.004450)	9895	0.00465	9865	0.00424	8190	0.00408	9835	0.00574	9995	0.00775
						9875	0.00451				

more nearly consistent than the data previously reported.[2] In Table I the data for the 77°F isotherm are in parentheses for pressures above 6,800 psia. These parenthetical values are non-equilibrium solubilities determined when the liquid phase co-existed with vapor and hydrate phases. The original purpose of this investigation was the study of vapor-liquid equilibrium. For those pressures at which the hydrate formed, samples of the liquid phase nevertheless were taken. However, the attainment of equilibrium in hydrate systems is a slow tedious process,[4] and the parenthetical values are therefore the solubilities measured before the hydrocarbon in the vapor phase had been completely transposed to the hydrate phase.

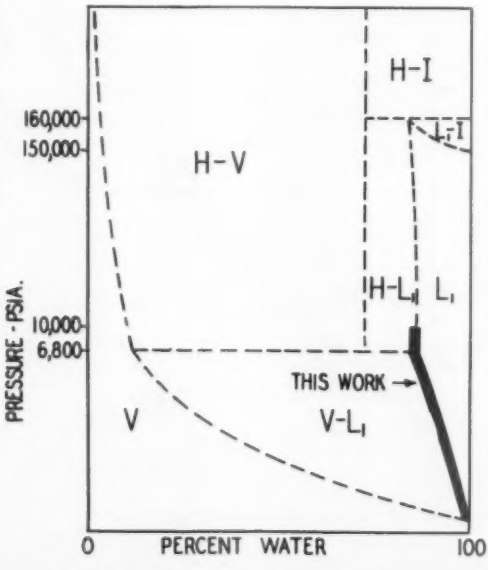

FIG. 2 — SCHEMATIC P-X DIAGRAM OF THE METHANE-WATER SYSTEM AT 77°F.

Kobayashi and Katz[4] reported the co-existence of vapor, hydrate, and liquid at 6,800 psia and 77°F; they also have presented a schematic P-T diagram of the methane-water system. Fig. 2 was prepared from this P-T diagram and shows a schematic P-X diagram of the methane-water system at 77°F. The heavy solid line indicates the location of the present work and illustrates clearly the solid hydrate-liquid water phase equilibria above 6,800 psia at 77°F. Because the equilibrium cell used in this investigation was not equipped with observation ports, the hydrate formation was noted by the anomalous behavior of the cell contents as compared with vapor-liquid equilibria.[4]

The smoothed values for the solubility of methane in water are given in Table II. The solubilities at 200 psia were obtained by interpolation between the authors' data and that of Winkler[1] at one atmosphere.

Fig. 3 is the temperature-solubility diagram for the methane-water system based upon the smoothed values. The exhibition of the minimum solubility phenomenon persists strongly at pressures to 10,000 psia. Comparison with the T-X diagram for the ethane-water system[3] shows that the minimum solubilities occur over about the same range of temperatures for the two systems. This would not necessarily have been expected, since the temperatures are very near to the critical of ethane and considerably removed from that of methane. Evidently the critical properties of the solute do not constitute a good basis for correlating solubility. As was discussed regarding the ethane-water system, for the higher pressures the methane-water system also shows the probability of a maximum solubility following the minimum solubility as the temperature is increased.

Comparison of the methane-water system with the ethane-water[3] and a natural gas-water[5] system is made in Fig. 4. At low pressures, the solubilities of the ethane and the methane are very nearly the same, the solubility of the methane being slightly greater at 500 psia. As the pressure increases, the solubility of the methane increases more than that of the ethane so that at 10,000 psia the solubility of the methane is more than twice that of the ethane. However, at one atmosphere the solubility of the ethane is 30 per cent greater than that of the methane.[7] The natural gas-water system shown

contained in part 88.51 per cent methane and 6.02 per cent ethane. Fig. 4 indicates that for the range of pressures shown the hydrocarbons are not additively soluble in the water independent of each other. If they were, the solubility of the natural gas should be the sum of that of the two hydrocarbons plus an allowance for the other hydrocarbons in the gas. Since the solubilities of the heavier hydrocarbons are as yet unknown, it cannot be determined whether or not the solubilities are additive on the basis of the composition of the solute gas. Some work on this basis in which the solubilities of the heavier hydrocarbons were extrapolated from those of the methane and ethane indicated that the solubility of a mixture is not additive on the composition basis. Such solubility extrapolations are hazardous, even within a given system; however, the effect of the solute's being a mixture of gases is noticeable. At the lower pressures, the solubility of the natural gas is greater than that of the pure methane. Since the ethane is, and the other hydrocarbons may be, nearly as soluble as the methane at low pressures, their presence increases the solubility of the natural gas to a value greater than that of the pure methane. At the higher pressures their relatively small solubility in comparison to methane decreases the solubility of the natural gas below that of the methane. The solubility is therefore an additive function; but until more data are available, the exact nature of that function cannot be determined.

It is often convenient in the oil or natural gas industries to have gas-liquid solubility data expressed in cubic feet of gas

Table II — Smoothed Values for the Solubility of Methane in Water in the Vapor-Liquid Region

Pressure psia	Mole Fraction $CH_4 \times 10^3$ 77°F	100°F	160°F	220°F	280°F	340°F
200	0.329	0.273	0.203	0.188	0.165	0.131
400	0.640	0.528	0.407	0.383	0.388	0.428
600	0.925	0.760	0.599	0.572	0.607	0.699
800	1.170	0.986	0.780	0.752	0.811	0.960
1000	1.380	1.199	0.945	0.930	1.016	1.230
1250	1.629	1.425	1.133	1.148	1.272	1.569
1500	1.862	1.620	1.308	1.339	1.521	1.895
2000	2.263	1.953	1.608	1.662	1.980	2.456
2500	2.588	2.247	1.861	1.961	2.359	2.945
3000	2.868	2.503	2.094	2.233	2.678	3.373
3500	3.110	2.738	2.309	2.478	2.984	3.770
4000	3.332	2.962	2.516	2.701	3.279	4.148
5000	3.724	3.360	2.888	3.100	3.815	4.849
6000	4.041	3.701	3.221	3.447	4.272	5.500
7000	4.312*	3.987	3.519	3.757	4.685	6.108
8000	.....	4.236	3.782	4.034	5.070	6.687
9000	.....	4.461	4.007	4.296	5.441	7.238
10000	.....	4.670	4.211	4.538	5.793	7.750
14.7	0.0186**	0.0010**				

*Hydrate-Vapor-Liquid Equilibrium at 6800 psia.
**Winkler[5]

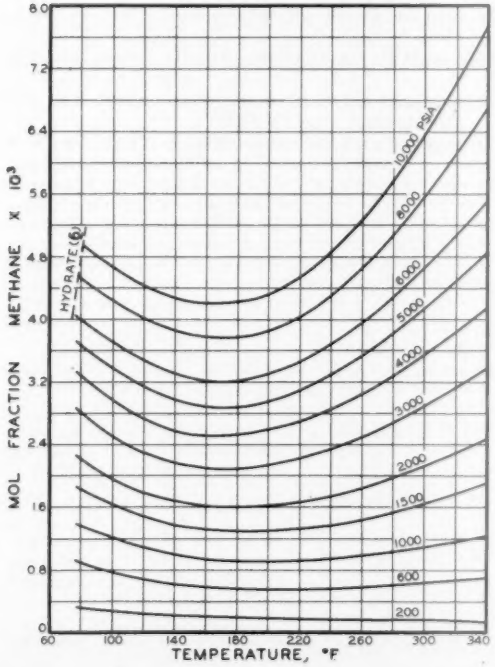

FIG. 3 — SOLUBILITY OF METHANE IN WATER AT CONSTANT PRESSURE.

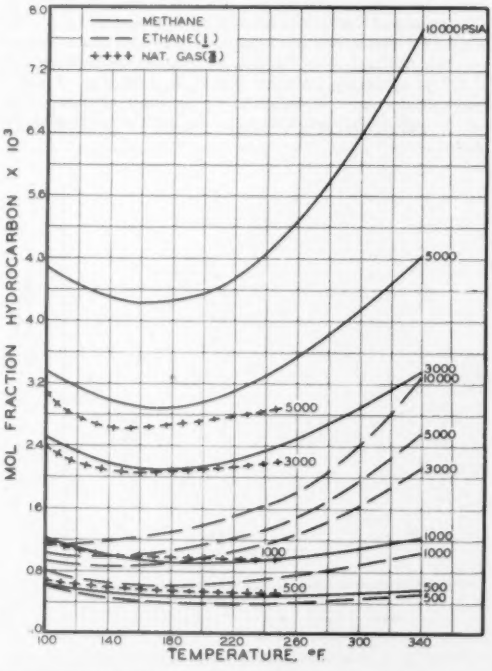

FIG. 4—COMPARISON OF SOLUBILITIES OF HYDROCARBONS IN WATER.

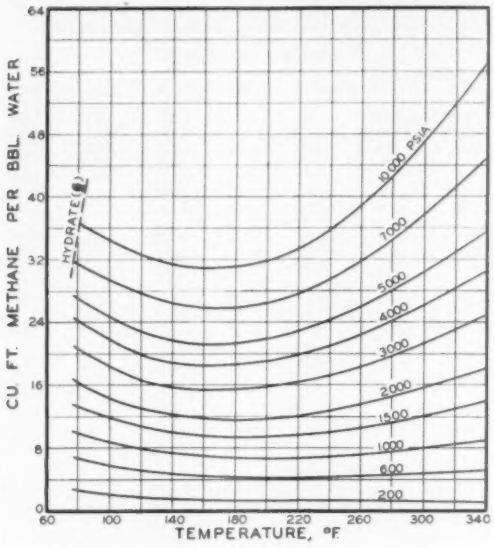

FIG. 5 — VOLUMETRIC SOLUBILITY OF METHANE IN WATER.

per barrel (42 gal) of liquid. This has been done in Fig. 5. The volume of methane is referred to 60°F and 14.7 psia. The curves for the various pressures have the same characteristics as those of Fig. 3, since the data for Fig. 3 were multiplied by 7.370 to obtain the data for Fig. 5. In both Figs. 3 and 5 the hydrate region is indicated on the basis of observations of the authors, but primarily upon the work of Kobayashi and Katz.[6]

MATERIALS

The water used was distilled, and deaerated by boiling before use. The methane used had the following composition as analyzed by the Gulf Oil Corp.: nitrogen, 0.27 per cent; carbon dioxide, 0.21 per cent; methane, 98.72 per cent; ethane, 0.60 per cent; propane, 0.13 per cent; butanes plus, 0.07 per cent.

ACKNOWLEDGMENT

The writers wish to express their appreciation to the Gulf Oil Corp. for extending the Gulf Oil Fellowship to Culberson for this investigation. The Phillips Petroleum Co. generously supplied the pure grade methane used in this work.

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RELAXATION METHODS APPLIED TO OIL FIELD RESEARCH

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ABSTRACT

A numerical method for solving partial differential equations in steady state fluid flow is described. This method, known as the "relaxation method," has two advantages over analytical methods: (1) practically any problem can be solved, and (2) a solution can be obtained quickly. A disadvantage is that the solution is not general. The method is applied to core analysis and relative permeability measurement to calculate constriction effects and to calculate the true pressure drop measured by a center tap in a Hassler type relative permeability apparatus. Further applications are suggested.

INTRODUCTION

Many problems in fluid flow cannot be solved analytically because of the nature of the boundary conditions. For many problems, however, an exact answer is not necessary because boundary conditions are not exactly defined or the parameters describing the porous medium are not accurately known. The relaxation method can be used to obtain an approximate answer easily and quickly for the flow of incompressible fluids in porous media. The method can also be used for other types of problems, such as determining the stress in a shaft under load, or the temperature distribution during steady state heat flow. In this discussion only calculations concerned with the flow of fluids in porous media will be considered. The method was introduced by R. V. Southwell in 1935.[1]

THEORY

The treatment given here follows that given by Emmons.[2] Consider a porous medium to be replaced entirely by a net of tubes of equal length and uniform cross-sectional area as shown in part in Fig. 1. Assume that the net of tubes behaves exactly like the porous medium which it replaces; that is, the net can be made fine enough to reproduce exactly the porous medium. Assume also that Darcy's Law can be used to calculate the flow from one point to another point through these tubes. The flow from point 1 to point 0 is

$$Q_{1,0} = \frac{KA}{\mu a}(P_1 - P_0) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where a is the distance between points; K is the "permeability" of a tube; A is the cross-sectional area of a tube; μ is the viscosity of the liquid in the porous medium; and $(P_1 - P_0)$ is the pressure difference between point 1 and point 0. In like manner the flow can be calculated from points 2, 3, and 4 to point 0. The net flow into point 0 is

$$Q_0 = \frac{KA}{\mu a}(P_1 + P_2 + P_3 + P_4 - 4P_0) \quad . \quad . \quad (2)$$

For an incompressible fluid the net flow into point 0 will be zero or, $Q_0 = 0$. This says that at point 0 fluid is neither being accumulated nor depleted. Therefore,

$$P_1 + P_2 + P_3 + P_4 - 4P_0 = 0 \quad . \quad . \quad . \quad . \quad (3)[3]$$

If, now, with specified boundary conditions, the pressure is known at a finite number of points in a given region, as at the points shown in Fig. 1, Equation (3) will be satisfied at every point. If, on the other hand, the pressure is not known, the pressure can be guessed at these points. Then, unless the guess is perfect, Equation (3) will not be satisfied at all of the points.

When Equation (3) is not satisfied, let

$$\delta = P_1 + P_2 + P_3 + P_4 - 4P_0 \quad . \quad . \quad . \quad . \quad (4)$$

where δ is an apparent error and is called the residual at point 0. Equation (4) shows how much the pressure guess is in error at point 0 with respect to the surrounding points. A positive residual means that the pressure is too low, and a negative residual means that the pressure is too high.

To bring the residual, δ, to zero in order to satisfy Equation (3), it is necessary to make changes in the pressure guesses. Equation (4) shows that a +1 change in P_0 will change the residual at point 0 by −4. A +1 change in the pressure at any of the four surrounding points will change the residual at point 0 by +1. Thus it can be seen that a change at any point will affect the residual at that point and the four surrounding points. By changing the pressure from point to point, all of the residuals can eventually be brought nearly to zero and the problem will be solved. This procedure is the essence of relaxation methods and is used to relax the residuals so that Equation (3) is satisfied at every point.

The procedure can be most easily explained in detail by solving a simple problem. As Southwell says, "To explain every detail of a practical technique is to risk an appearance of complexity and difficulty which may repel the reader. A

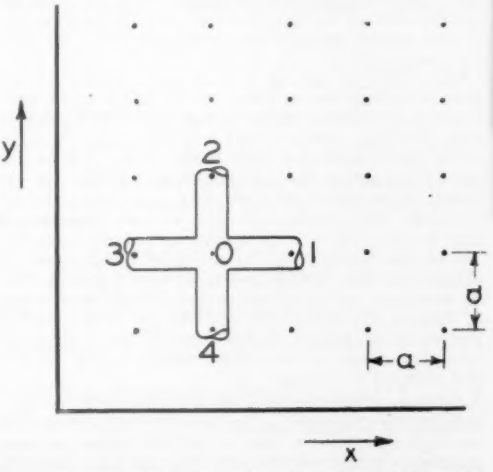

FIG. 1 — REPRESENTATION OF A POROUS MEDIUM BY A NETWORK OF CONDUCTING TUBES.

[1] References given at end of paper.

Manuscript received in the office of the Petroleum Branch September 10, 1950. Paper presented at the Petroleum Branch Fall Meeting in Los Angeles, Calif., Oct. 12-13, 1950.

[3] In the Appendix Equation (3) is shown to be approximately equivalent to Laplace's equation.

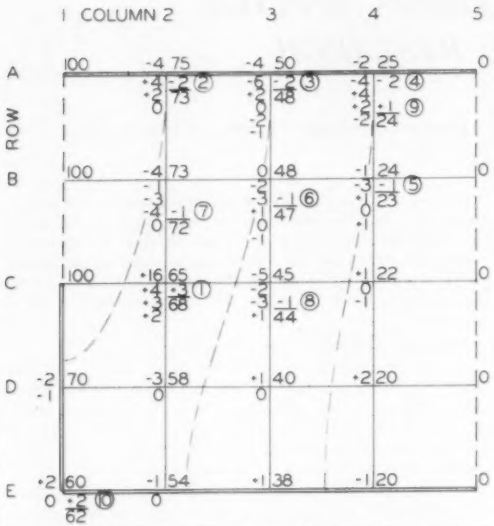

FIG. 2a — APPROXIMATE SOLUTION OF A TWO DIMENSIONAL FLOW PROBLEM WITH THE LEFT FACE PARTLY OBSTRUCTED.

verbal description of the tying of a 'reef knot' would make that simple operation appear quite formidable."

APPLICATIONS

Two-Dimensional Fluid Flow

The first problem that will be solved is a two-dimensional fluid flow problem as shown in Fig. 2a. The upper and lower boundaries are impermeable, and the lower half of the left face of the porous medium is also impermeable. Pressure is applied to the left face, and the flow per unit K/μ and per unit thickness of the porous medium is to be calculated. In order to calculate the flow, it is only necessary to know the average pressure over any plane surface parallel to the right boundary.[3]

The problem is laid out to scale with sufficient room to make the calculations as shown in Fig. 2a. A square grid, known as a relaxation pattern, is laid out on the drawing. A coarse net (few points) is used first. The known pressures, which for this problem are the pressure on the right face, 0, and the pressure on the upper half of the left face, 100, are written in just above and to the right of the point to which they refer. Dimensionless pressures are used. Equipotential lines are sketched in to the best of the calculator's ability. The pressure is then guessed at each point. Fig. 2a shows the equipotential lines and the guesses. Residuals are calculated for each point not on the impermeable boundaries according to Equation (4) and are placed to the left of the pressure guesses. If the pressure is known exactly for a particular point, for example, on the inflow boundary in Fig. 2a, then that point has no residual.

Residuals at the boundaries can be calculated in two ways. Both ways are illustrated in the solution of this problem. For the upper boundary the image of the plane below the upper boundary is mapped onto the plane above the upper boundary. This mapping in no way changes the problem because the upper impermeable boundary which is a streamline remains a streamline when the lower plane is folded 180° onto the upper plane. Equation (4) becomes

$$\delta = P_1 + P_2 + 2P_4 - 4P_0 \quad . \quad . \quad . \quad . \quad . \quad . \quad (4a)^*$$

because $P_2 = P_0$. Equation (4a) is now used to calculate the residuals on the upper boundary. The above method for calculating residuals is preferred because all residuals can then be directly compared.

The second method of calculating residuals is illustrated for the lower boundary and the boundary on the left side where the residuals are obtained by assuming that the tube along the impermeable boundary has one-half the area of the tubes connecting the points inside the boundaries. The flow from point 1 to point 0 on the lower boundary is then

$$Q_{1,0} = \frac{1}{2}\,\frac{KA}{\mu a}\,(P_1 - P_0) \quad . \quad . \quad . \quad . \quad . \quad . \quad (1a)$$

and similarly for flow from point 3. Equation (2) for the net flow into point 0 on the lower boundary becomes

$$Q_0 = \frac{KA}{\mu a}\left(\frac{1}{2}P_1 + P_2 + \frac{1}{2}P_3 - 2P_0\right) = 0 \quad . \quad (2a)$$

so that the equation for calculating residuals along the lower boundary is

$$\delta = \frac{1}{2}P_1 + P_2 + \frac{1}{2}P_3 - 2P_0 \quad . \quad . \quad . \quad . \quad . \quad (4b)$$

For points along the left boundary the equation is

$$\delta = P_1 + \frac{1}{2}P_2 + \frac{1}{2}P_4 - 2P_0 \quad . \quad . \quad . \quad . \quad . \quad (4c)$$

and for the corner point

$$\delta = \frac{1}{2}P_1 + \frac{1}{2}P_2 - P_0 \quad . \quad . \quad . \quad . \quad . \quad . \quad (4d)$$

Equations (4b), (4c), and (4d) are now used to calculate the residuals at points on the lower boundary and on the left boundary. The problem now has been set up with the pressure estimates and the calculated residuals.

To relax** the residuals, one begins by changing the largest residual first. If a residual is surrounded by residuals of the same sign, the correction is usually made large enough to change the sign of the residual but to leave its magnitude about the same. This is called "over-relaxing." If a residual is surrounded by residuals of opposite sign, the correction is usually less than that required to bring the residual to zero.

In Fig. 2a the largest residual is at point *C-2* (row *C*, column 2); therefore, this residual was changed first. The order in which the residuals were changed is given by the circled numbers. Because the residual at point *C-2* is surrounded by residuals of opposite sign, a correction of +3 (instead of +4) is placed under the pressure estimate, which adds −12 to the residual at the point (making the residual +4) and adds +3 to each of the surrounding residuals. The new residuals are placed under the old residuals, the addition being made mentally. The second change is made at point *A-2*. Here a correction of −2 is placed under the pressure estimate, which changes the residual by +8 and adds −2 to the residual on the right and to the residual below.

Relaxation thus proceeds from point to point until all of the residuals have been relaxed to a minimum. After relaxation is complete, the corrections are added to the original pressure guess. It will be noted that the original pressure guess is not changed during the relaxation procedure. Only after relaxation is complete are the corrections added to the original guess. The solution is shown in Fig. 2a.

The flow through the section without the impermeable

*Note that the subscripts refer to the exact arrangement of the points shown in Fig. 1. Point 0 does not refer to a specific point but refers to any point in the relaxation pattern.

**The grid with the original guesses, some or all of which are in error, may be thought of as being under a strain. The process of solution is one of relaxing these strains nearly to zero.

boundary at the left side is

$$Q = \frac{KA\triangle P}{\mu L} = \frac{100KA}{\mu L}$$

The flow through the constricted section is calculated from the average pressure drop between the right hand side and the first line of points. The average pressure along the first line of points is 21.7. The flow through the constricted section then is

$$Q = \frac{21.7\ KA}{\mu\frac{L}{4}} = \frac{86.8\ KA}{\mu L}$$

so that the ratio of constricted flow to unconstricted flow is

$$\frac{Q_c}{Q} = \frac{86.8}{100} = 0.868$$

A more exact answer can be obtained by advancing to a finer mesh and increasing the number of points. An additional calculation was made with points placed in the center of the grid squares of Fig. 2a. The new grid lines connecting the points on the finer net are not parallel, but are at an angle of 45° to the grid lines connecting the points on the coarse net used first. The relaxation procedure, however, is carried out in the same manner. The results of the calculations are shown in Fig. 2b. The average pressure across the same plane as used for calculating the results from Fig. 2a is 21.0. The ratio of constricted flow to unconstricted flow is therefore

$$\frac{Q_c}{Q} = 0.84$$

The exact answer calculated analytically is 0.820.

The time required to obtain the two solutions by one experienced in relaxation methods is approximately as follows:

1. To set up the problem, sketch in the streamlines, and guess the pressures — 15 minutes.
2. To calculate and relax the residuals — 20 minutes.
3. To check for errors and calculate the answer — 10 minutes.
4. To set up the problem on a finer net and to calculate and relax the residuals again — 30 minutes.

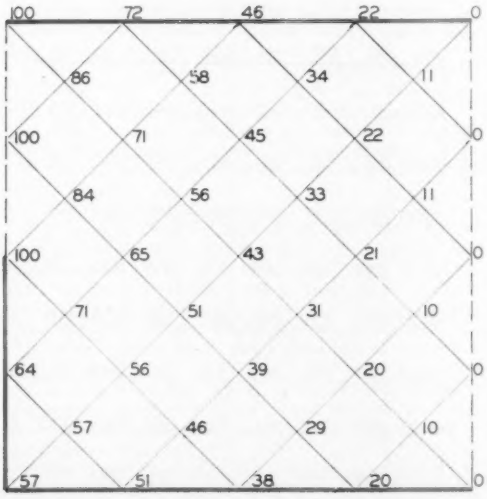

FIG. 2b — ADVANCE TO A FINER NET FOR THE PROBLEM ILLUSTRATED IN FIG. 2a.

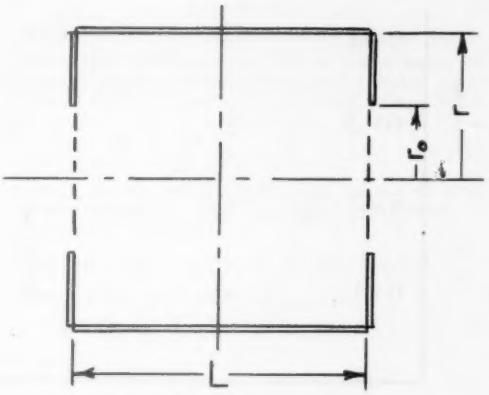

FIG. 3 — EXAMPLE OF THREE DIMENSIONAL FLOW WITH AXIAL SYMMETRY.

5. To check for errors and calculate the answer — 15 minutes.

The time required to obtain an answer on the coarser mesh was 45 minutes, and on the finer mesh, 45 minutes. The total time required to obtain an answer within three per cent was 90 minutes. The time required to set up the problem and to sketch in the equipotential lines as accurately as possible is usually well spent. A poor guess could easily double the time required to relax the residuals.

Three-Dimensional Flow with Axial Symmetry

An example of three-dimensional flow is shown in Fig. 3, where a cylindrical core has its two faces partially obstructed so that axial symmetry is preserved. This problem may be solved in two dimensions on a plane through the axis of the core, but the relaxation equations will be different than those for the previous example. Only one-quarter of the section through the axis is used because of symmetry.

From the relaxation equation derived in the Appendix, the following equation is obtained for calculating the residuals for this example

$$\delta = P_1 + P_2 + P_3 + P_4 - 4P_0 + \frac{1}{2n}(P_2 - P_4) \quad . \quad . \quad (5)$$

where P_0 is in the n'th row from the axis of the cylindrical core, as shown in Fig. 4. Equation (5) is the same as Equation (4) with the added terms $\frac{1}{2n}(P_2 - P_4)$. This means that the residuals are calculated in the same manner as for the two-dimensional problem but with the above term added to each residual.

Equation (5) can be rewritten as

$$\delta = P_1 + \left(1 + \frac{1}{2n}\right)P_2 + P_3 + \left(1 - \frac{1}{2n}\right)P_4 - 4P_0 \quad . \quad (5a)$$

This equation shows that a change in P_2 will affect the residual at point 0 by $\left(1 + \frac{1}{2n}\right)$ times the change in P_2 and a change in P_4 will affect the residual at point 0 by $\left(1 - \frac{1}{2n}\right)$ times the change in P_4. The relaxation equation for points on the center line is

$$\delta = P_1 + 4P_2 + P_3 - 6P_0 \quad . \quad . \quad . \quad . \quad . \quad . \quad (5b)$$

The solution of a problem where $L = 2r$ and $r_0 = \frac{3}{4}r$ is given in Fig. 5. The average pressure on the first line of points

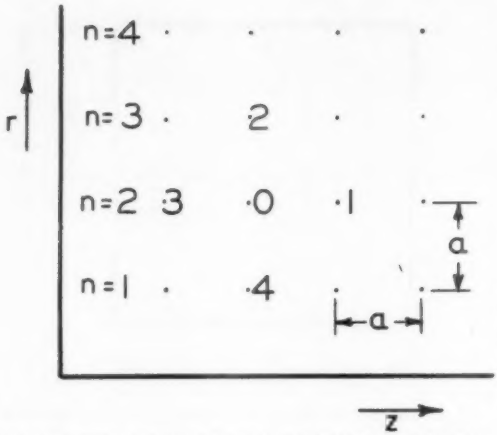

FIG. 4 — REPRESENTATION OF THREE DIMENSIONAL FLOW WITH AXIAL SYMMETRY.

from the right side is 117. For an unconstricted core the pressure would be 125. The ratio of constricted flow to unconstricted flow is therefore

$$\frac{Q_c}{Q} = \frac{117}{125} = 0.935$$

For this problem a more exact answer was obtained by using a finer net. A coarse net was used first. After the pressure was determined for each of the points on the coarse net, interpolation gave the pressures at intermediate points on the finer net. Residuals were calculated for the points on the finer net and were relaxed again to obtain the final solution.

Advancing to a finer net to get a more exact answer does not require a finer net over the whole region.[1] Usually a finer net is placed only in a region of high potential gradient. With additional points placed on only part of the region, a great deal of labor can be saved during the solution of a problem. The answer obtained is just as accurate as an answer obtained by using the finer net over the whole region.

FURTHER APPLICATIONS

Core Analysis

The example worked out in the previous section can be extended to calculate the ratio of constricted flow as a function of the open per cent area of the core face. Two additional calculations were made and the results are shown in Fig. 6. The calculated per cent constricted flow is not exact because a fine enough mesh was not used. However, the results are believed to be within three per cent of the exact ratio.

The curve of Fig. 6 can be used to determine the constriction to flow when a core face is partly covered by a porous plate that is symmetrically placed with respect to the axis. Such a setup is used in some types of relative permeability measurements. Homogeneous permeability is assumed and the diameter of the core is equal to its length. The results can also be applied to determine the effect of partly covering a core face with wax during routine permeability measurements of cores.

Another application of relaxation methods is found in relative permeability work where the pressure in the wetting phase is measured by center taps whose permeability is usually the same as the permeability of the porous end plates. Calculations were made by relaxation methods to obtain the true pressure drop as a function of the ratio of the permeability of the porous end plate to the permeability of the core. The schematic diagram and results of the calculations are shown in Fig. 7.

The problem was solved with the following conditions and assumptions:

1. Core diameter equals core length.
2. A particular end plate configuration is used as shown in Fig. 7.
3. The core has homogeneous permeability.
4. Infinitesimal thickness of paste for capillary contact is used between core and plate.
5. Fluid connection between end plate and center tap is through the core only.

Only if all these assumptions are true can the pressure correction given in Fig. 7 be applied quantitatively for the relative permeability setup used. However, pressure corrections can be calculated for any ratio of core length to core diameter and any end plate configuration. For assumptions different than those given in Items 3, 4, and 5, only qualitative statements can be made. If a core contains bedding planes parallel to the axis of the core, and if permeability perpendicular to the bedding plane is much less than the permeability parallel to the bedding plane, the pressure correction will be greater than that given in Fig. 7. If a finite thickness of paste with a conductivity greater than that of the porous end plate is used for capillary contact, the correction will be less than that given in Fig. 7.

Nonisotropic Permeability

Problems involving nonisotropic permeability can also be handled by relaxation methods. Referring to Equation (1) and Fig. 1, let the permeability in the x-direction be m times the permeability in the y-direction, or

$$K_x = mK_y$$

The net flow into point 0 will be

$$Q_o = \frac{mK_yA}{\mu a}(P_1 - P_o) + \frac{K_yA}{\mu a}(P_2 - P_o) + \frac{mK_yA}{\mu a}(P_3 - P_o) + \frac{K_yA}{\mu a}(P_4 - P_o) \quad . \quad . \quad . \quad (6)$$

or

$$Q_o = mP_1 + P_2 + mP_3 + P_4 - 2(1+m)P_o = 0 \quad . \quad (7)$$

784	745	665	566	458	345	230	115	0
826	767	675	570	460	346	231	115	0
1000	827	699	581	465	349	232	116	0
1000	850	716	591	471	352	234	117	0
1000	860	726	599	476	356	236	118	0
1000	865	733	605	481	359	238	119	0
1000	867	736	609	484	361	240	120	0
1000	868	738	611	486	362	241	120	0
1000	869	739	612	487	363	241	120	0

r

z

FIG. 5 — APPROXIMATE SOLUTION TO PROBLEM ILLUSTRATED IN FIG. 3.

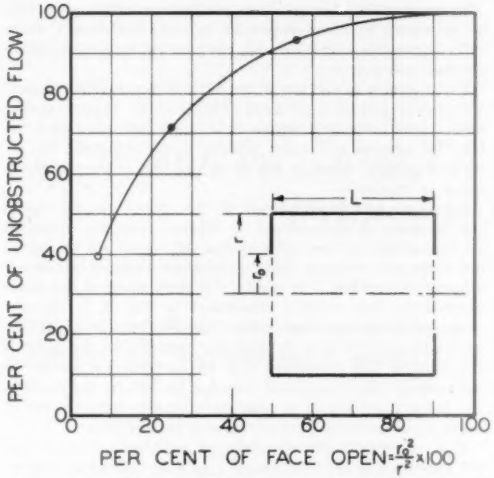

FIG. 6 — PER CENT OF UNOBSTRUCTED FLOW AS FUNCTION OF THE PER CENT OF FACE OPEN FOR CYLINDRICAL CORE WHOSE FACES ARE SYMMETRICALLY OBSTRUCTED.

so that the equation for calculating residuals becomes

$$\delta = mP_1 + P_2 + mP_3 + P_4 - 2(1+m)P_0 \quad . \quad . \quad (8)$$

Other types of inhomogeneity can also be handled by the proper substitution for K in Equation (1).

SUMMARY

Relaxation methods have many applications in oil field research. They not only can be used to obtain solutions for problems in fluid flow, but can be used to obtain a solution to almost any potential problem, such as the potential distribution between two or more electrodes, or the temperature distribution in steady state heat flow.

In conclusion, the steps required to obtain a solution are briefly summarized as follows:

1. Draw to scale the region for which the pressure distribution is desired. Make the drawing large enough to leave plenty of space for relaxing the residuals.
2. Place a square grid system, or relaxation pattern, on the drawing. Use a coarse net for the first approximation.
3. Place the known pressure points on the drawing.
4. Sketch in equipotential lines as accurately as possible.
5. Guess the pressures at the remaining points.
6. Determine the relaxation equations and calculate the residual at each point.
7. Relax the residuals starting with the largest residual first. In general, when a change of one-half makes the surrounding residuals larger, the residuals have reached a practical minimum.
8. If a residual is surrounded by residuals of the same sign, make the correction large enough to change the sign of the residual but to leave its magnitude about the same. This is known as "over-relaxing" and enables one to arrive at a solution more rapidly.
9. If a more accurate answer is desired, or a region of high potential gradient is to be studied, advance to a finer net. A finer net is sometimes necessary only in the region of high potential gradient.
10. Determine intermediate pressures by interpolation and repeat steps 6 and 7.
11. Check for errors. If any are found, relax the residuals again.

APPENDIX
DERIVATION OF RELAXATION EQUATIONS

During flow of incompressible fluids in porous media, the pressure distribution resulting from applied boundary conditions must satisfy Laplace's equation, which in two dimensions is

$$\frac{\partial^2 P}{\partial x^2} + \frac{\partial^2 P}{\partial y^2} = 0 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

Laplace's equation can be replaced by an approximately equivalent equation by letting derivations be represented by finite difference equations.

Referring to Fig. 1 in the text, the first derivative, $\frac{\partial P}{\partial x}$ between points 0 and 1 can be expressed as

$$\left(\frac{\partial P}{\partial x}\right)_{0\text{-}1} \cong \frac{P_1 - P_0}{a} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

and between points 3 and 0 as

$$\left(\frac{\partial P}{\partial x}\right)_{3\text{-}0} \cong \frac{P_0 - P_3}{a} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

where a is the spacing between the points. The second derivative can be expressed as

$$\left(\frac{\partial^2 P}{\partial x^2}\right) \cong \frac{\left(\frac{\partial P}{\partial x}\right)_{0\text{-}2} - \left(\frac{\partial P}{\partial x}\right)_{3\text{-}0}}{a} = \frac{P_1 + P_3 - 2P_0}{a^2} \quad . \quad (4)$$

In like manner,

$$\left(\frac{\partial^2 P}{\partial y^2}\right)_0 \cong \frac{P_2 + P_4 - 2P_0}{a^2} \quad . \quad . \quad . \quad (5)$$

Substituting Equations (4) and (5) in Equation (1) gives

$$P_1 + P_2 + P_3 + P_4 - 4P_0 = 0 \quad . \quad . \quad . \quad . \quad . \quad (6)$$

When Equation (6) [Equation (3) in text] is satisfied by a finite number of points, Laplace's equation will be solved approximately.

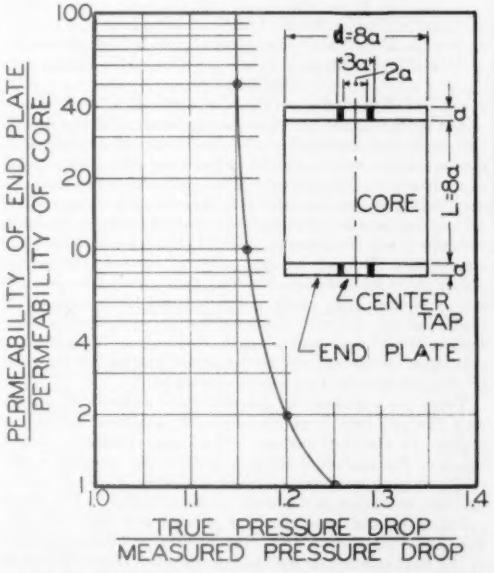

FIG. 7 — TRUE PRESSURE DROP MEASURED BY A POROUS CENTER TAP IN A HASSLER TYPE RELATIVE PERMEABILITY SETUP.

Laplace's equation in cylindrical coordinates is

$$\frac{\partial^2 P}{\partial r^2}+\frac{1}{r}\frac{\partial P}{\partial r}+\frac{\partial^2 P}{\partial z^2}+\frac{\partial^2 P}{\partial \theta^2}=0 \quad . \quad . \quad . \quad . \quad (7)$$

With axial symmetry, $\frac{\partial^2 P}{\partial \theta^2}=0$, so that Laplace's equation may be simplied to

$$\frac{\partial^2 P}{\partial r^2}+\frac{1}{r}\frac{\partial P}{\partial r}+\frac{\partial^2 P}{\partial z^2}=0 \quad . \quad . \quad . \quad . \quad . \quad (8)$$

From Equations (2), (3), and (4), and Fig. 4, the following equations may be derived:

$$\left(\frac{\partial^2 P}{\partial r^2}\right)_o \cong \frac{P_2+P_4-2P_o}{a^2} \quad . \quad . \quad . \quad . \quad . \quad (9)$$

$$\frac{1}{r}\left(\frac{\partial P}{\partial r}\right)_o \cong \frac{1}{r_o}\,\frac{P_2-P_4}{2a} \quad . \quad . \quad . \quad . \quad . \quad . \quad (10)$$

$$\left(\frac{\partial^2 P}{\partial z^2}\right)_o \cong \frac{P_1+P_3-2P_o}{a^2} \quad . \quad . \quad . \quad . \quad . \quad (11)$$

Substituting Equations (9), (10), and (11) in Equation (7),

$$\frac{1}{a^2}(P_1+P_2+P_3+P_4-4P_o)+\frac{1}{r_o}\,\frac{1}{2a}(P_2-P_4)=0 \quad . \quad (12)$$

Let $r_o = na$, where a is the grid spacing. Then

$$P_1+P_2+P_3+P_4-4P_o+\frac{1}{2n}(P_2-P_4)=0 \quad . \quad . \quad . \quad (13)$$

For the axis where $r=0$, $\frac{1}{r}\left(\frac{\partial P}{\partial r}\right)\rightarrow\frac{\partial^2 P}{\partial r^2}$ as $r\rightarrow 0$ so that Equation (8) becomes

$$2\left(\frac{\partial^2 P}{\partial r^2}\right)+\frac{\partial^2 P}{\partial z^2}=0 \quad . \quad . \quad . \quad . \quad . \quad . \quad (14)$$

Substituting Equations (9) and (11) in Equation (14) and observing that $P_2 = P_4$

$$P_1-4P_2+P_3-6P_o=0 \quad . \quad . \quad . \quad . \quad . \quad . \quad (15)$$

REFERENCES

1. Southwell, R. V.: *Relaxation Methods in Theoretical Physics*, Oxford Press (1946).
2. Emmons, H. W.: *Trans.* ASME (1943) **65**, 607.
3. Muskat, M.: *Flow of Homogeneous Fluids Through Porous Media*," J. W. Edwards, Inc., Ann Arbor, Mich. (1946) 163.

DISCUSSION

By T. J. Nowak, Union Oil Co. of Calif., Member AIME

The authors made an ingeneous application of the relaxation method of Southwell to the steady state flow of fluids in porous media. As a matter of interest, the relaxation method is a recent development which has already emerged as an essential weapon of research. It is effective on problems which are difficult to solve or cannot be solved by orthodox analysis. Therefore, its introduction to oil field research is a noteworthy contribution. Through its application to Hassler type permeability study its usefulness has been demonstrated by pointing out to us the errors which are introduced by the customary neglect of the distortion produced in the equipotential lines. Review of the paper will be made on the basis of qualitative evaluation of the various mathematical procedures that can be used for solving the problems presented.

There are available, in general, three methods of solving fluid flow problems in porous media: an analytical solution, a solution by electrical analogy, and an approximate numerical solution. The analytical solution involves the orthodox application of pure mathematics based on purely abstract reasoning with no regard to the limits of uncertainties in the physical data. Its aim is to obtain a general and exact solution. Because of the abstract reasoning involved and the complexity of the final solution as well as the excessive time required to make the calculations, the analytical analysis has not been widely applied. As to the electrical analogy approach, it is often used either as an auxiliary tool of the analytical method or for solving problems impossible to solve analytically. However, it requires expensive and complicated equipment which normally rules it out.

It is common to use one of the various approximate numerical and/or graphical solutions. They provide a quick answer within some prescribed degree of accuracy but suffer from the fact that general and exact solution is not obtained. The relaxation method is one of the latest and best of the numerical solutions available.

Emphasis has been placed in the paper on the speed and accuracy of this method. It appears from the approach used in getting at the problems that the significant advantage lies in the revolutionary change of outlook which is introduced towards the problem. For example, in the solution of the three-dimensional flow problem illustrated in Fig. 3, it becomes evident that the attention is fixed not on the wanted equipotential line distribution through the core but on the data of the problem. The computer's task was to assume a pattern on the basis of all the physical intuition he has on the problem and bring unaccounted or residual quantities within specified range of uncertainty, thus accounting for the data.

It is unfortunate that the orthodox analytical approach was not presented to the problem of Fig. 3 as this would clearly show how the abstract mathematical outlook is transformed by the relaxation method into a tangible outlook. However, one can refer to the paper, "Flow Into Slotted Liners and an Application of the Theory to Core Analysis" by C. R. Dodson and W. T. Cardwell, Jr., reported in Vol. 160, AIME *Transactions*, in which an analytical approach was presented to essentially the same problem as in Fig. 3. The exceptions were that a cubical core was used whose face was obstructed by rectangular strips extending symmetrically from the opposite edges of the core's face. The results obtained give the same conclusions which can be drawn from the curve in Fig. 6.

In conclusion, I would like to inquire if the authors have considered solution of nonsteady state flow problems in porous media by the relaxation method and, if so, would they present a list of things to be considered in applying this method to nonsteady state problems?

AUTHORS' REPLY TO MR. NOWAK

We wish to thank Mr. Nowak for his thoughtful comments. His question concerning the application of the relaxation method to nonsteady state flow problems can be answered as follows:

The relaxation method differs from other numerical methods in that it permits the "relaxation" of a "strain" which exists between the correct answer and an assumed answer. It is true that computation with a "strain," a small number, is easier than computation with the variable possessing the strain which is ordinarily a much larger number, and this is one reason for the applicability of the relaxation method; however, the real reason is that relaxing permits the elimination of a difference between the correct answer and an assumed answer. For steady state flow, the correct "answer" is known to be that the sum of all the flow into and out of a point in a grid must be zero. For an assumed answer, the net flow into or out of each point is calculated, usually quite easily, and its difference from zero is the "strain" which must be relaxed. Relaxation is accomplished by changing the pressure at the grid point which affects the "strain" in a known way.

For nonsteady state flow such a procedure is not possible, because we cannot compute the strain. We do not know beforehand the extent to which the flow into a point should be greater than or less than zero; hence we do not know the extent to which an assumed answer differs from the correct answer. ★ ★ ★

THE PHASE BEHAVIOR OF A NATURAL HYDROCARBON SYSTEM

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ABSTRACT

The phase behavior of a naturally occurring hydrocarbon system whose critical temperature is near the reservoir temperature has been described.

The same volume per cent liquid was observed for the first time at three different pressures for isotherms immediately below the critical temperature. The shapes of the isothermal equilibrium constant curves necessary to predict this phenomena are discussed and illustrated.

INTRODUCTION

The phase behavior of a number of hydrocarbon systems has been reported; however, very little data are available on natural occurring hydrocarbon systems whose critical temperature is near the reservoir temperature. This appeared to be the case for the fluid studied here; therefore the pressure-volume-temperature data for this system were determined for presentation.

METHOD

The PVT data were obtained with equipment similar to that described by Weinaug and Katz,[1] consisting principally of a two-section, double-windowed gauge mounted in a constant temperature air bath. The procedure followed was essentially that used by Katz and Kurata[5] except that a cathetometer, reading direct to 0.01 cm, was used to determine the height of each extreme phase limit.

The system studied was formed by recombining vapor and liquid samples from the first stage separator of the well. Portions of these samples were displaced with mercury into the cell which had previously been filled with mercury. A predetermined amount of the liquid sample was introduced, while an excess of vapor was admitted. The resulting mixture was brought to equilibrium at the condition of the separator during sampling. By adding mercury to maintain the pressure, enough vapor was displaced to give a gas/oil ratio within the cell equal to that produced by the separator at the time of sampling. The remaining material was then considered to be equivalent to the reservoir fluid. An analysis of material in the cell, computed from analysis of vapor and liquid samples and the separator gas/oil ratio, is given in Table I.

Table I — Composition of Hydrocarbon System

Component	Mole Per Cent
Carbon Dioxide	0.13
Nitrogen	0.76
Methane	53.91
Ethane	14.20
Propane	9.64
Iso Butane	1.25
Normal Butane	4.29
Iso Pentane	1.12
Normal Pentane	1.87
Hexane	2.72
Heptanes +	10.11
Molecular Weight of Heptanes +	178.50

[1]References given at end of paper.

Manuscript received in the office of the Petroleum Branch August 5, 1950. Paper presented at the Fall Meeting of the Petroleum Branch in New Orleans, La., Oct. 4-6, 1950.

Pressure volume determinations were made under isothermal conditions for the recombined sample. The pressure on the reservoir fluid was increased by addition of mercury until a single uniform phase existed within the cell. Temperature of the air bath was adjusted to the desired value and maintained constant for a period of at least three hours before any measurements were made. The bubble or dew point pressure was then found by the removal of small quantities of mercury until the first indication of a second phase appeared. Pressure was recorded and then reduced further by the withdrawal of additional quantities of mercury. Between each removal, vapor and liquid within the cell were brought to equilibrium by rocking the air bath. After establishing equilibrium, the volume of each phase was determined as described above.

EXPERIMENTAL RESULTS

The data obtained for the isotherms have been tabulated in Table II, plotted in Fig. 1, and cross plotted in Fig. 2 to give the familiar pressure-temperature phase diagram. The 196.2, 201.3, 212.4 and 226.4°F isotherms exhibited normal behavior of hydrocarbon systems above their critical temperatures. Nothing unusual was observed in the determination of the 80.5, 101.2 and 121.1°F isotherms. However, the 141.0, 161.0, 170.9, 181.0 and 191.2°F isotherms showed phase behavior which the authors believe has not been reported previously. As the pressure was reduced, a small quantity of vapor formed when the system entered the two-phase region. This quantity of vapor continued to increase rapidly at the expense of the liquid phase with only slight reduction in pressure. Vaporization continued until a maximum volume per cent vapor was reached, and from this point further decrease in pressure produced condensation. The quantity of liquid increased at the expense of the vapor phase; however, larger reductions in pressure were necessary than were required initially to produce a comparable phase change. This last behavior is identical to retrograde condensation and progressed as pressure was

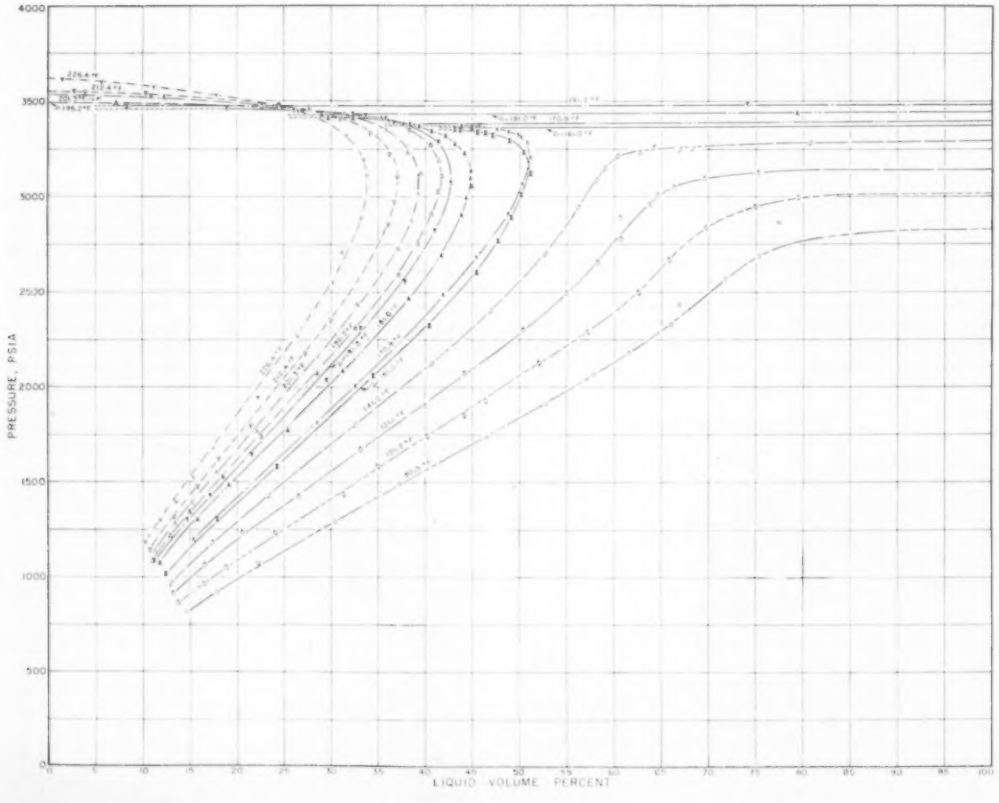

FIG. 1 — PERCENTAGE LIQUID ISOTHERMS.

Table II — Experimental Phase Data

Pressure psia	Vol. of System cc	Vol. of Liquid cc	Volume Per Cent Liquid
	Temperature 80.5°F		
2855			Single Phase
2825			Definite Separation
2690	30.1	22.6	75.2
2570	30.6	22.0	71.7
2435	31.3	21.0	66.9
2330	32.1	21.2	66.0
2180	33.7	20.7	61.5
2070	35.1	20.3	57.8
1915	37.3	19.7	52.8
1735	41.0	19.0	46.4
1495	48.0	17.9	37.2
1290	57.4	17.4	30.4
1070	70.8	15.7	22.2
915	84.3	15.0	17.8
815	98.3	14.3	14.6
	Temperature 121.1°F		
3175			Single Phase
3170			Two Phases
3150			Two Phases
3140			Two Phases
3125	31.0	23.3	75.2
3090	31.2	21.7	69.5
3045	31.5	20.9	66.3
3005	31.7	20.5	64.6
2955	31.9	20.3	63.7
2885	32.3	19.5	60.6
2780	33.0	20.0	60.6
2655	33.8	19.7	58.2
2490	35.1	19.3	54.9
2290	37.3	18.8	50.3
2065	41.0	18.1	44.1
1900	44.0	17.5	39.9
1670	50.4	16.7	33.1
1425	60.2	16.0	26.5
1230	71.2	14.6	20.5
1060	84.1	13.9	16.5
910	100.2	13.3	13.2
	Temperature 161.0°F		
3375			Single Phase
3365			Two Phases
3355	32.8	14.8	45.0
3350	32.8	14.1	43.1
3345	32.8	14.3	43.7
3340	32.8	14.9	45.5
3335	32.8	15.2	46.3
3320	32.9	15.5	47.2
3295	32.9	16.1	49.0
3230	33.2	16.8	50.5
3125	33.8	17.3	51.1
3015	34.4	17.2	50.1
2890	35.4	17.3	49.1
2765	36.5	17.4	47.6
2605	38.0	17.2	45.3
2320	41.5	16.8	40.5
2060	46.4	16.0	34.5
1580	61.2	14.9	24.3
1305	75.2	13.4	17.8
1015	100.0	12.4	12.4

Pressure psia	Vol. of System cc	Vol. of Liquid cc	Volume Per Cent Liquid
	Temperature 101.2°F		
3040			Single Phase
3015			Two Phases
2995	30.3	24.1	79.3
2945	30.4	22.8	74.9
2835	30.8	21.5	69.6
2670	31.7	20.4	65.8
2500	32.9	20.5	62.5
2290	34.8	19.9	57.1
2130	37.1	19.3	51.9
1930	40.2	18.6	46.3
1855	41.8	18.5	44.0
1740	44.4	17.8	40.1
1585	49.3	17.2	34.9
1435	55.1	17.2	31.2
1230	65.8	15.8	24.0
1050	78.8	14.8	18.8
960	87.1	14.3	16.4
860	99.8	13.7	13.7
	Temperature 141.0°F		
3360			Single Phase
3285	31.9	25.7	80.7
3255	32.0	20.5	64.0
3255	32.1	21.9	68.2
3250	32.0	21.4	66.9
3235	32.0	20.1	62.7
3210	32.1	19.4	60.2
3150	32.4	19.1	58.9
3090	32.7	19.0	58.1
2945	33.5	18.8	56.2
2705	35.2	18.5	52.6
2405	37.9	17.8	46.9
2125	42.6	17.3	40.6
1805	49.8	16.2	32.5
1430	64.1	14.9	23.3
1180	79.7	13.8	17.3
965	100.0	13.0	13.0
	Temperature 170.9°F		
3410			Single Phase
3395			Single Phase
3380	31.1	11.7	37.6
3370	31.1	13.6	43.8
3365	31.1	14.3	45.8
3355	31.1	14.8	47.6
3340	31.2	15.2	48.8
3325	31.2	15.6	49.8
3310	31.3	15.7	50.1
3285	31.4	15.9	50.7
3205	31.9	16.3	51.1
3070	32.6	16.4	50.3
2910	33.8	16.5	48.8
2690	35.7	16.2	45.3
2485	37.6	15.8	41.9
2005	45.8	14.9	32.6
1810	50.7	14.3	28.5
1195	80.0	12.2	15.3

Table II — Continued

Pressure psia	Vol. of System cc	Vol. of Liquid cc	Volume Per Cent Liquid
	Temperature 181.0°F		
3465		Single Phase	
3445	33.6	26.7	79.4
3430	33.6	9.7	28.9
3420	33.7	10.0	29.6
3415	33.7	10.9	32.3
3395	33.8	12.0	35.6
3380	33.9	13.0	38.3
3370	34.0	13.4	39.3
3345	34.0	13.9	40.6
3320	34.2	14.4	42.0
3280	34.3	14.8	43.1
3225	34.6	15.3	44.1
3140	35.1	15.7	44.8
3100	35.4	15.9	44.8
3055	35.9	16.1	44.9
2995	36.4	16.1	44.4
2910	37.0	16.2	43.8
2700	39.0	16.2	41.5
2460	41.8	16.0	38.3
2090	48.7	15.3	31.3
1775	57.5	14.5	25.3
1490	69.1	14.3	19.2
1305	80.1	12.6	15.8
1070	99.9	11.7	11.7
	Temperature 196.2°F		
3495		Two Phases	
3490	33.5	2.4	7.1
3470	33.5	7.6	22.6
3405	33.9	12.0	35.3
3350	34.2	13.1	38.3
3270	34.6	14.0	40.5
3190	35.0	14.5	41.3
3105	35.6	14.8	41.6
3025	36.3	15.0	41.2
2910	37.4	15.2	40.6
2755	39.0	15.3	39.1
2595	40.8	15.2	37.2
2310	44.8	14.6	32.5
2070	49.9	14.2	28.4
1730	59.9	13.5	22.6
1530	68.4	12.5	18.3
1335	79.4	11.9	15.0
1215	88.0	11.3	12.8
1080	99.9	10.9	10.9
	Temperature 212.4°F		
3560		Single Phase	
3555	34.8	0.9	2.7
3550	34.8	1.4	3.9
3540	34.8	3.6	10.3
3480	35.1	9.5	24.3
3410	35.5	11.0	31.0
3335	36.0	12.3	34.1
3225	36.7	13.3	36.2
3105	37.6	13.9	37.0
2970	39.0	14.3	36.7
2855	40.1	14.4	36.0
2355	46.8	14.0	30.0
2180	50.5	13.7	27.2
1800	61.2	13.1	21.4
1625	68.5	12.3	18.0
1480	75.6	11.9	15.8
1315	85.3	11.4	13.3
1140	99.7	10.6	10.7
3495			
3485	33.3	24.7	74.1
3475	33.4	2.8	8.3
3465	33.4	6.3	18.9
3450	33.4	8.7	26.1
3435	33.5	10.1	32.3
3425	33.6	11.3	33.7
3405	33.6	12.0	35.7
3370	33.8	13.0	38.4
3290	34.2	14.1	41.3
3075	35.6	15.2	42.8
2995	36.2	15.3	42.3
2825	37.8	15.5	41.0
2695	39.2	15.5	39.6
2555	40.8	15.5	37.9
2305	44.3	14.7	33.1
2030	50.2	14.3	28.5
1640	62.7	13.5	21.5
1425	74.5	12.5	17.2
1300	80.6	11.9	14.7
1070	99.8	11.1	11.1
	Temperature 201.3°F		
3565		Single Phase	
3530	34.6	3.7	10.7
3520	34.6	4.2	12.2
3490	34.8	8.5	24.4
3460	34.8	9.6	27.6
3435	35.0	11.0	31.4
3350	35.4	12.7	35.8
3230	36.2	14.0	38.7
3120	37.0	14.6	39.4
3010	38.0	14.9	39.1
2870	39.2	15.1	38.5
2725	40.8	15.1	37.1
2430	44.6	14.6	32.7
2160	50.1	14.2	28.5
1760	61.5	13.6	22.0
1550	70.2	12.5	17.8
1390	79.4	12.2	15.3
1280	86.5	11.6	13.4
1135	99.4	11.0	11.1
	Temperature 226.4°F		
3625		Single Phase	
3615	35.5	0.5	1.4
3600	35.5	2.0	5.6
3575	35.6	4.0	11.1
3535	35.8	6.4	17.8
3450	36.3	9.6	26.4
3325	37.1	11.7	31.5
3200	38.0	12.7	33.4
3115	38.7	13.1	33.8
2890	41.0	13.4	33.2
2710	43.1	13.4	31.1
2555	45.2	13.6	30.1
2275	50.0	13.2	26.4
1950	58.6	13.0	22.2
1685	68.0	11.9	17.5
1525	75.6	11.6	15.3
1395	83.2	11.2	13.5
1300	90.0	10.6	11.8
1180	100.2	10.3	10.3

reduced until a maximum volume per cent liquid was reached. Normal vaporization took place with further pressure reduction until the system filled the cell.

DISCUSSION OF RESULTS

The system studied exhibited unusual behavior only in the region below the critical temperature, and therefore the discussion will be limited to these data. The discussion above shows that as pressure on this system is increased, normal condensation takes place until a maximum percentage of liquid is formed. At this point further increase in pressure causes the percentage of liquid to decrease: retrograde phenomenon. The liquid volume continues to decrease until it reaches a minimum value, at which point further pressure increments result in large increases in the percentage of liquid, and the system passes into the single phase region through a bubble point. This new behavior will be referred to as *renascent* vaporization or condensation.

This new phenomenon is probably related to data obtained by Eilerts, Barr, Mullens and Hanna,[3] who noted the existence of two liquid phases in the region of critical temperature. Also it might be a degeneration of that observed by Kay.[2] These data are plotted in Fig. 3.

Interesting possibilities develop in the consideration of shapes of equilibrium constant *vs* pressure curves, necessary to predict renascent behavior at constant temperature. As pressure is increased from a low value, equilibrium constants for hydrocarbon systems decrease, as shown in Fig. 4, points *A* to *B* for each curve. This trend continues until a minimum value is reached for each curve except methane, (see points *B*). With rising pressure, all methane curves determined to date show a continuous decrease in the equilibrium constant value. These decreasing constants indicate normal condensation when pressure is raised. After minimum values are reached in the curves for constituents heavier than methane, equilibrium constants increase as pressure is raised. This trend continues to denote normal behavior until rate of change in curves for heavier constituents counteracts the diminishing values for methane. For further additions of pressure the curves then indicate retrograde behavior, which progresses until the system passes into the single phase region. However, in this case the retrograde behavior gives way to rapid condensation when pressure is raised.

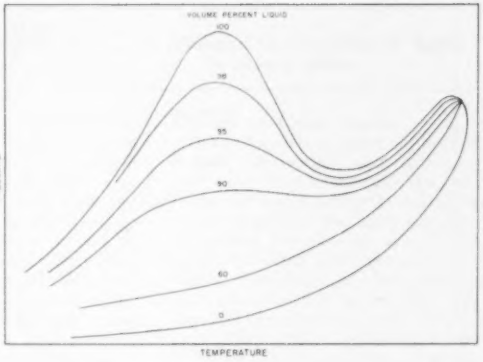

FIG. 3 — PHASE DIAGRAM OF A HYDROGEN AND A PETROLEUM NAPHTHA.

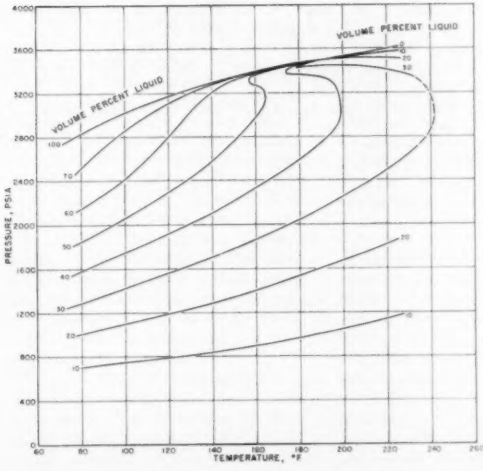

FIG. 2 — PHASE DIAGRAM OF A NATURAL HYDROCARBON SYSTEM.

This new behavior could be predicted by the use of several types of equilibrium constant curves. First, if an inflection occurred in the curves for heavier constituents, such as illustrated by points *C* and the dotted lines in Fig. 4, the rate at which equilibrium values for heavier components increased would subside and allow the decreasing values for methane to become dominant again. Thus, condensation would be indicated for further rises in pressure. It should be noted that these inflections would have a tendency to cause the curves to diverge rather than converge, as denoted by the convergence pressure concept.

Another type of curve which would indicate this behavior is already apparent in the values for methane reported by Standing and Katz.[4] With rising pressures the methane curves tend to level off and values shown become almost constant, (see points *A* to *B*, Fig. 5). This change results in the prediction of retrograde behavior at lower pressures. However, at higher pressures a point of inflection occurs, (point *B*), with a sudden decline in equilibrium values for methane, even though pressures are rising steadily. This rate of decrease could be sufficient to overcome the effect of the increasing equilibrium constants for heavier constituents, and thus renascent vapori-

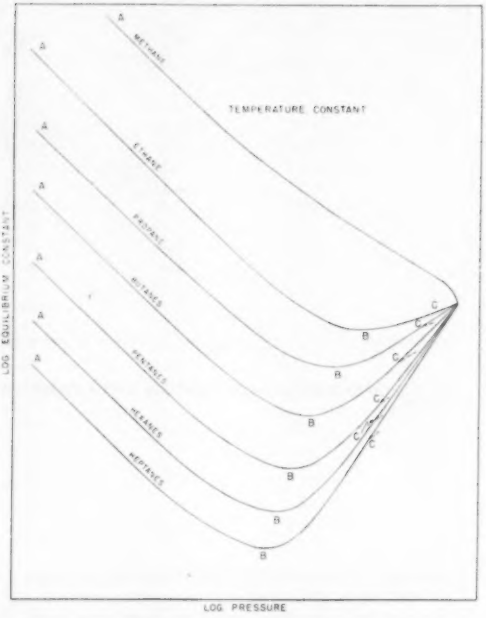

FIG. 4 — CHANGES IN EQUILIBRIUM CONSTANTS WITH PRESSURE.

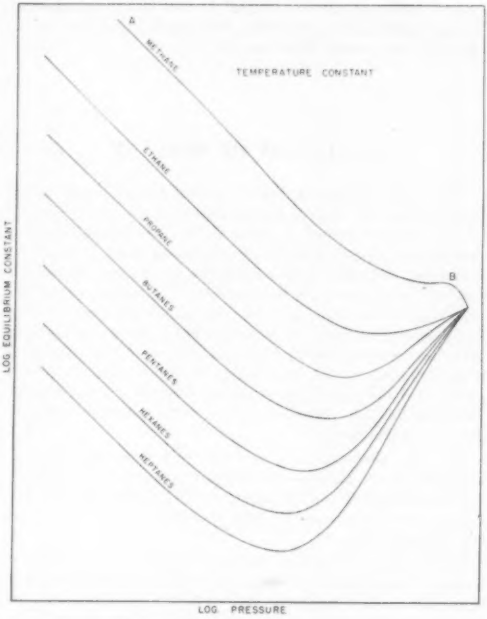

FIG. 5 — CHANGES IN EQUILIBRIUM CONSTANTS WITH PRESSURE.

zations would be indicated. Since methane is present in a much greater quantity than any other constituent, small changes in values for the methane equilibrium constant will produce large changes in the indicated phase behavior.

It is probable that the curves which may be used to predict renascent vaporization or condensation will be some combination of the two types presented above.

ACKNOWLEDGMENT

The authors of this paper wish to acknowledge the cooperation and support of the Department of Petroleum Engineering and the Bureau of Engineering Research of the University of Texas, under whose auspices the work was done.

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★ ★ ★

The Drift of Things

. . . as followed by **EDWARD H. ROBIE**
Secretary AIME

Finding Summer Jobs

Though organized only three years ago, the Institute's Minerals Beneficiation Division is one of its most active groups. Among its committees is the Education Committee, which one might perhaps be pardoned for thinking would have more or less prosaic activities. But under the chairmanship of Rush Spedden, at MIT, it is really doing a job that other committees might emulate. It has tackled the problem of summer jobs for students.

Its plan is designed (1) to help students find suitable summer jobs so that they can get some valuable working experience while earning money to help meet the rapidly increasing cost of an education; and (2) to give the mining and metallurgical companies of this country a chance to have a wider choice of technical employes. Through a few months of summer work a company may easily appraise the capabilities of a man they may wish to employ later. The student himself may discover an interesting problem for a thesis or special project for his senior year.

AIME Fall Meetings

Owing to the fact that the usual Fall Meeting, or Mid-Year Meeting, or Regional Meeting, as it was variously called, was not held in 1950, many AIME members are wondering if any definite policy has been adopted as to its continuance. Although scheduling of the Fall Meeting is done on a year-to-year basis, there is no ground for the idea that such meetings will not be held at least fairly regularly in the future. Last year a combination of circumstances prevented holding such a meeting. The American Mining Congress held an important convention and exhibition at Salt Lake City at the end of August. The AIME was to hold its Annual Meeting in St. Louis in February, 1951. To hold another national meeting in the Mid-West or Far West in the interval between seemed, especially with a war going on, to be putting somewhat of a strain on the membership, both in preparing for and attending such a meeting.

This year the Fall Meeting is being resumed, of course, with the Mexico City meeting, Oct. 29 to Nov. 3. Next year, the Fall Meeting will be held in Chicago, sometime in the week beginning Sept. 8. This is the time of the Centennial of Engineering celebration, which the American Society of Civil Engineers is sponsoring in connection with its 100th anniversary. Many engineering societies will hold their fall meetings in Chicago at that time, so that papers of general interest, or joint interest with other groups, will be especially appropriate. Several AIME Divisions are likely to participate in the program, though few have made a definite decision as yet. No plans have yet been made for the Fall Meeting of 1953, so that invitations will be considered from any Local Section or city that wishes to sponsor a meeting at that time. A suggestion has been made that it be held in Montreal, with a field trip to some of the Canadian mining properties.

As to Annual Meetings, the present plan is to alternate them between New York and another city: New York 1948, San Francisco 1949, New York 1950, St. Louis 1951, New York 1952, Los Angeles, 1953, New York 1954, possibly Houston or some other petroleum center 1955, New York 1956, possibly Chicago 1957.

More Peeves

In the June issue we spoke of some words and phrases that got under our skin a bit. Robert A. Laurence, from Knoxville, Tenn., voices "a loud and hearty amen. I wish you had included two of my pet peeves: 'Finalize' (to complete or finish) and 'foreseeable future'." (At what point does the unforeseeable future begin—five minutes from now, five days, five weeks, or five months?) But wasn't it President Harding who thought up 'normalcy,' for the 1920 campaign?" Yes, it surely was; we gave the credit to Coolidge.

And here is as good a chance as any to protest against the growing tendency among people that should know better — many of them university graduates — to use the word "I" when they should say "me." We have a memorandum on our desk which says, "Mr. Peirce wants to get together with you and me right after lunch Wednesday." This use of the word "I" in the objective case crops up in letters and speech several times a week. Perhaps it results from lack of instruction in grammar in the grade schools. But how anybody can get through high school and college and remain so illiterate we cannot understand.

Chance to Clean House

Out in the country where we live the serenity has recently been punctured more often than formerly by the bells of the junkman's truck. It used to be that payment for scrap metal was little or nothing, the junkman charging as much for taking away the stuff that neither of us wanted as he was willing to give for the stuff that he could use. Anything of heavy metal now seems to be in demand, and the junkman's face lit up no end when we found an old cast iron stove for him. This led us to look into the situation a bit, and we find that steel producers are really threatened with a scrap shortage as serious as that which occurred about 10 years ago. Supplies of heavy industrial iron and steel scrap are dangerously low. Scrap inventories have dropped from two months' supply to sufficient only for a few days or weeks, according to the American Iron and Steel Institute.

Of the 1.5 billion tons of steel now in use in the United States, millions of tons normally are discarded each year and eventually return to the mills as scrap. During World War II between 110 and 120 million tons was diverted overseas, and scarcely any ever came back to this country. Scrap has not recently been exported in any quantity, but the country's immense steel production, at the rate of 104 million tons a year, exceeding by 10 per cent the World War peak, has absorbed an enormous amount of scrap. Producers would like to have about 60 per cent scrap and 40 per cent virgin metal to make steel to the best advantage; currently the proportions are substantially reverse.

The scrap cycle, steel from mill to product and back to mill, must be restored quickly to maintain current production to say nothing of building up depleted inventories to carry mills through the winer months when collections fall off. Government, industry, and agriculture can aid in war preparedness and provide a public service by conducting an emergency inspection of their properties and sending obsolete machinery and equipment to the nearest scrap dealer. There will be no better time for housecleaning than now, in spite of the shortage of labor in many plants. All available heavy scrap is urgently needed. ★ ★ ★

Personals

K. MARSHALL FAGIN has been appointed manager of the oil loan division in the investment department of Southwestern Life Insurance Co. He will function in the appraisals and evaluation of oil producing properties on which the company has received loan applications.

Fagin was graduated from the University of Illinois in 1930 with a degree in petroleum engineering. He served as a trainee engineer with Shell Petroleum Corp. at Seminole, Okla., and from 1931 to 1935 was engaged in general field engineering with Tide Water and Stanolind in the East Texas Field. He came to Dallas in 1935 as assistant to the chief petroleum engineer of the Magnolia Petroleum Co. and continued in that position until 1945, when he became associated with the magazine *Petroleum Engineer* as editor of the drilling and production department.

+

VANCE J. DRISCOLL, junior petroleum engineer, Stanolind Oil and Gas Co., has been transferred from Lovington, N. Mex., to Henderson, Tex.

+

HARVEY B. ELDER, JR., has been promoted to the position of assistant drilling foreman by the Ohio Oil Co., Hobbs, N. Mex.

+

DAN GILLETT is now employed by Fraser, Burr and Olyphant, Midland, Tex.

+

ROBERT P. RIDLEY has resigned from The Texas Co. to accept a position with J. R. Butler & Co., Houston.

+

PHIL RENN, formerly with Cardinal Chemicals, Inc., is now in charge of the newly established Gulf Coast office of Oil Base, Inc. Renn is a graduate in chemical engineering from Rice Institute, and has also been employed in drilling operations with Lago Petroleum Corp. in Venezuela and as sales engineer for Baroid Sales Division.

MAC D. OLIVER, formerly with Cable & Stine, Wichita Falls, Tex., is now associated with the San Juan Oil Co. as chief engineer. Oliver graduated from Texas A&M College with a BS degree in petroleum engineering in 1940. He served in the U. S. Army and was released as a lieutenant-colonel. Oliver will reside in Dallas.

+

CHARLES L. LOCKETT, JR., is now president, Esso Standard, Inc., Cairo, Egypt.

+

EWELL B. MARTIN, JR., has become associated with the Sun Oil Co., Silver, Tex.

+

GREGOR C. MERRILL, formerly with United Overseas Petroleum Co., Paris, is now located in New York with the California Texas Oil Co.

+

DOMINGO NORIEGA has become assistant of the technical production department of the Ministry of Mines and Hydrocarbons for the Venezuelan government petroleum branch at Caracas.

+

ARTHUR V. THOMPSON has recently accepted an appointment with the Carter Oil Co., Tulsa, as a computer trainee.

+

SAM P. LEEMAN of Dallas has been recalled to active military service for an indefinite period.

+

CHARLES S. YUST has become associated with the Humble Oil and Refining Co., Houston.

+

JULIAN E. HUZAREVICH of Stanolind Oil and Gas Co., is now at Tulsa, Okla. He had been in the Lubbock, Tex., office.

+

WILLIAM ARTHUR AUSTIN, JR., has become associated with the Creole Petroleum Corp., Caracas, Venezuela.

+

WILLIAM EMMETT BROWN has been made assistant district superintendent, Sohio Petroleum Co., Lafayette, La. He was previously with the Mid-States Oil Corp., Tulsa, Okla.

+

WILLIAM E. RICHARDS is now employed by the Rock Hill Oil Co., San Antonio.

E. T. HECK has accepted a position with the Minard Run Oil Co., where he will be in charge of geology and engineering. He previously held a similar position as chief geologist for the Quaker State Oil Refining Corp. His new address is Box 18, Bradford, Pa.

+

WALTER C. PEARSON has been promoted to the position of assistant division engineer, Stanolind Oil and Gas Co., Oklahoma City, Okla.

+

JOE A. PEERY, Sunray Oil Corp., has been transferred from Alice, Tex., to Lake Charles, La.

+

Four personnel promotions and transfers were recently announced by National Geophysical Co., Inc., Dallas, Tex. R. L. BOULWARE was promoted from party chief to supervisor, National Geophysical Co. of Canada, Ltd. CORBY HART was transferred from National Geophysical Co. of Canada, Ltd., and promoted to supervisor in National Geophysical Co., Dallas. E. L. CAMPBELL has been transferred to Midland, Tex., and promoted to supervisor in charge of West Texas operations. J. H. FRAZER was promoted to supervisor in National Geophysical Co. of Canada, Ltd.

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JAS. D. HUGHES, general sales manager of Lane-Wells Co. has been elected a director of Lane-Wells Co. to fill a vacancy on the board, according to Walter T. Wells, chairman. Hughes has been associated with the company since 1939 and was Gulf Coast division sales manager of the company in Houston from 1941 to 1945, when he was transferred to Los Angeles as manager of oil field sales. Early in 1945 he was made sales manager and in 1950 became general sales manager.

Natural Gas Industry

(Continued from Page 12, Section 1)

However, a series of court decisions, beginning in 1942, led the Commission to believe that it could assert jurisdiction over the producing and gathering properties of interstate pipe line companies because of the absence of arm's-length bargaining in negotiations for the gas supply. It then limited returns from such properties to about 6 per cent of the depreciated investment involved. This, in effect, fixed the wellhead price of the gas.

It was in 1947 that the fears of the independent producers were first aroused. The language of the U. S. Supreme Court in its decision in the case of *Interstate Natural Gas v. Federal Power Commission* led some, but not all, to believe that the door had been opened for Commission regulation of arm's-length sales by independent producers. Thus, nine years after the Natural Gas Act had been passed, a cloud was cast over the correctness of the Commission's policies and practices.

After the Interstate case, independent producers had good reason to fear that the Federal Power Commission would set aside their arm's-length contracts with interstate transporters and fix field prices which would allow the independent producers a return of only 6 or 6½ per cent on their successful ventures. This, in some cases, would amount virtually to confiscation of the producer's gas reserves. To allay these widespread fears, the Federal Power Commission hastened to assure independent producers that it had no intention of regulating them. To make its intention official, the Commission on August 7, 1947, issued what came to be known as Order 139. In this order, the Commission stated it was of "the opinion that it was the intent of Congress that the control of production and gathering of natural gas should remain a function of the states and that the Natural Gas Act should not provide for regulation of those subjects," and added:

"The Commission gives its assurance to independent producers and gatherers of natural gas that they can sell at arm's-length and deliver such gas to interstate pipe lines and can enter into contracts for such sale without apprehension that in so doing they may become subject to assertion of jurisdiction by the Commission under the Natural Gas Act."

Despite this official order, however, independent producers continued to take a skeptical view of the matter. It was realized that any order issued by the Commission could, likewise, be rescinded at any time by that Commission. Some producers did enter into contracts after the issuance of Order 139, believing or trusting that the Commission would abide by its order. The fears of the independent producers soon were intensified, however, when it became known that a majority of the Commission had no intention of abiding by this order.

It was recognized by the independent producers that the only satisfactory solution to the problem was legislation to clarify and affirm the intent of the Natural Gas Act. Finally, during the 81st Congress, the Kerr Bill was introduced in the Senate, and in an amended form passed both Senate and House. The purpose of the Kerr Bill was simply to re-state the original intent of Congress in the Natural Gas Act of 1938.

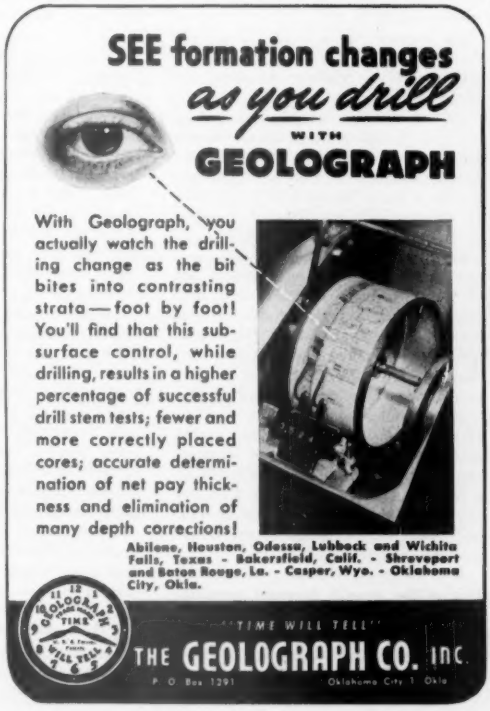
Then, on April 15, 1950, the President vetoed the Kerr bill.

Within less than 90 days, the Federal Power Commission rescinded its Order 139, and announced simultaneously its intention to promulgate rules and regulations pertaining to the independent producers of natural gas.

Such encroachments by a Federal agency in the field of free competitive business is harmful to the national economy and security, and is detrimental to the continued stability and progress of the oil and gas industry. Thus, the producer of a basic commodity, such as natural gas, a vital mineral resource, may be subjected to direct or indirect public utility regulation, with utter disregard for the competitive and risk-taking nature of his business. The application of the policy of a 6 or 6½ per cent return on the depreciated investment in producing properties and gathering facilities would result in varying prices being paid for gas in the same field, penalizing the efficient and rewarding the inefficient. There could be no surer way to stifle the incentive for exploration and development, and to jeopardize the long-range supply of natural gas.

It is entirely illogical to single out natural gas for regulation when the production and prices of all other competitive fuels are uncontrolled and unregulated. It is even more illogical when it is considered that natural gas is one of a mere handful of commodities that you can buy today cheaper than in 1938 (Fig. 6). During the past 12 years, since the passage of the Natural Gas Act, the price of gas to the average domestic consumer has decreased 12 per cent, while the price of coal has increased by more than 60 per cent.

Natural gas has a definite and important role in our national economy. If left to grow in an open competitive field, subject only to supply and demand effects and unhampered by federal control, the industry should continue its expansion to the common betterment of the industry, the public and the nation. ★ ★ ★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Proposed Changes To AIME Bylaws

The following amendments to the Bylaws of the AIME were considered by the Board of Directors at its meeting on June 13, and are being published in the August issues of the Institute journals, preliminary to a vote thereon at the meeting of the Board on Sept. 12:

To eliminate the privilege now given Student Associates of paying annual dues of $2 without a journal subscription:

Amend Article I, Sec. 8, as follows by deleting the italicized words in the second sentence: "A full-time student in good standing in an approved school, who has been nominated by at least three instructors of the nominee (one of whom must be an Institute member), may affiliate with the Institute as a Student Associate by payment of $4.50 annual fee, for which he shall receive a subscription to one monthly journal and be privileged to attend meetings of the Institute and to use the Engineering Societies Library and the Personnel Service; *provided however, that for Student Associates who do not elect to receive a monthly journal, the annual fee shall be $2.*"

To provide for a credit of $2 on the initiation fee for each year of enrollment as a Student Associate or Junior Member:

Amend the first sentence of Article II, Sec. 1, by adding the italicized words in the following: "Each newly-elected Member or Associate Member, and each Junior Member at the time of his transfer into the class of Member or Associate Member, shall pay, immediately upon notification of such election or such transfer, an initiation fee of $20; provided, however, that said initiation fee may be payable, at the option of the applicant, in four equal annual installments, the first of which shall be due upon notification of election or transfer; *and provided further that, beginning Jan. 1, 1952, a credit of $2 towards the initiation fee be granted for each year up to ten of uninterrupted and continuing membership as a Student Associate or Junior Member, or both. When such credit is allowed, no installment payments of the initiation fee shall be granted.*"

The following changes, to take effect at the annual business meeting, February, 1952, are made necessary by the revised procedure of the Nominating Committee in naming a President-elect instead of a President. (Currently there is a transition period in which both a President and President-elect are being named for 1952.)

Amend Article VI, Sec. 1, paragraphs 1 and 2 to read: "The number of Directors of this Corporation is 27, consisting of one President, one President-elect, one Past President, six Vice-Presidents, and 18 other Directors, to be elected as hereinafter provided; and in addition the Chairman of each duly constituted professional Division of the Institute, ex officio, shall serve as a Director, with full voting power, during his term as Chairman.

"At the regular November meeting of the Board of Directors or Executive Committee, the chairman thereof shall declare to be elected, as provided in Article XI of these Bylaws, nine Directors, of whom one shall also be designated as President-elect, and of whom two shall be designated as Vice-President. The nine Directors, including the Directors designated as officers, together with the newly elected Division Chairman in their capacity as ex-officio Directors, shall take office at the annual business meeting of the Institute next following the meeting at which they were declared elected. The term of all nine elected Directors shall be for a period of three years; provided, however, that the terms of the President-elect and President shall each be for one year, the President thereupon serving one year as Past-President."

Amend Article VI, Sec. 2, paragraph 1, sentences 2 and 3 to read as follows: "The President shall be that Director who, in the preceding year, served as President-elect. The President shall be ineligible to hold that office again until two years after the expiration of his term as President."

Amend Article VI, Sec. 3, to read as follows: "In the event of a vacancy occurring in the Board of Directors by death, resignation, promotion by election as President, President-elect, or Vice-President, or for any other reason than retirement at the end of three years' service, the remaining members of the Board shall elect a successor to fill the vacancy and to serve for the unexpired term. A member of the Board whose term has not expired and who is elected President-elect or Vice-President at an annual election shall be considered to have vacated his former office, and the Board shall fill the vacancy as above provided."

A proposed change in Article I, Sec. 5, sentence 2, clarifies the meaning formerly expressed: "He shall not have passed his 30th birthday anniversary at the time his application is received, and shall not remain a Junior Member beyond his 33d birthday anniversary, except that the Board of Directors shall have the power to waive the age limitation in the case of veterans from military service." Omit as obsolete: *This last requirement shall take effect January 1, 1950.*

A proposed change in Article VI, Sec. 5, sentence 2, recognizes the new office of Controller, approved by the Board at its meeting on Feb. 12, 1950: "Also, the Board may, upon nomination by the Treasurer, appoint one or more persons to perform the duties of Assistant Treasurer and of Controller."

A proposed change in Article VIII, Sec. 2, paragraph 3, sentence 5, sets a more practical time for the Board to pass on the final annual budget: "The Directors shall pass on this budget at their first open meeting after the annual business meeting of the Institute, modifying it as they consider necessary, and make definite detailed appropriations for the current calendar year."

A proposed change in Article VIII, Sec. 4, sentence 1, eliminates the requirement that the Admissions Committee be limited to eight members: "The Committee on Admissions shall consist of at least eight members of the Institute, the chairman and at least one other member being chosen from the Board of Directors, and shall be appointed by the Board, on recommendation of the President, at the first meeting of the Board after the annual business meeting of the Institute."

A proposed change in Article IX, Sec. 1, eliminates the second sentence, as no longer applicable. It reads: "In 1951 the Nominating Committee shall also select, as one of the nine Directors, a President to take office in February, 1952."

A proposed change in Article IX, Sec. 2, paragraph 2, sentences 4 and 5, eliminates a provision in the current bylaws that did not prove practical but maintains its intent: "In selecting candidates the Committee shall be guided by such rules of procedure as may from time to time be established by the Board; provided, however, that of the eight Directors in addition to the President-elect, a sufficient number be selected on the basis of geographical districts so that each such district will have at least one representative. The basis of selection of the others shall be at the discretion of the Committee."

A proposed change in Article XI, Sec. 4, paragraphs 3, 4 and 5, eliminates the requirement that Student Chapter officers, Faculty Sponsors, and Counselors all be required to make annual written reports to the Board:

"Each Student Chapter at its annual election shall choose an AIME member to be its Faculty Sponsor and forward his acceptance to the Secretary of the Institute. It shall be the duty of the Faculty Sponsor to promote the best interests of both the Student Chapter and the Institute and to make written reports of his stewardship to the Directors of the Institute as desired.

"It shall be the duty of the President of the Student Chapter and its Faculty Sponsor to secure, through the Local Section in whose territory it is situated, the appointment of a member of the Institute in the practicing profession to serve as Counselor for the Student Chapter, and to forward his acceptance to the Secretary of the Institute. It shall be the duty of this Counselor to promote cordial relations between the practicing engineers and the Student Chapter and to make written reports of his stewardship to the Directors of the Institute as desired.

"It shall be the duty of each Student Chapter to report promptly to the Secretary of the Institute the results of elections of officers, and to make written reports of activities to the Directors of the Institute as desired."

Opinions of AIME members on these proposed changes are invited and will be submitted to the Board before voting on Sept. 12. A copy of the current bylaws will be sent to any AIME member on request. ★ ★ ★

University Press Offers Oilfield Watercolors

A portfolio of eight landscapes and portraits by the New Mexican artist Peter Hurd has been published by the University of New Mexico Press. Of particular interest to Petroleum Branch members is "The Wildcat Well," a twilight scene in watercolor.

Other pictures in the portfolio are typical Southwestern scenes done in watercolor, tempera or charcoal. The reproductions were done by a deep-tone offset color process, and are suitable for framing 12 by 16 inches. The set sells for $12.50, and may be obtained from The University of New Mexico Press, Albuquerque, N. M. ★ ★ ★

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Employment Notices

The JOURNAL will post notices of men and jobs available. Companies and AIME members are invited to use this space, for which there is no charge. Except as noted below, address replies to: Code (appropriate number), JOURNAL OF PETROLEUM TECHNOLOGY, 601 Continental Bldg., Dallas 1. Show return address on envelope. These replies will be forwarded unopened and no fees are involved.

PERSONNEL

♦ Engineer, petroleum production, registered, presently employed, desires responsible position with aggressive independent or small producing company. Twelve years' experience mid-continent area all phases of production, specializing water flooding. Age 32, married. Code 150.

♦ Oilfield executive, graduate civil engineer with 12 years' foreign and domestic experience in oilfield management and various phases of petroleum engineering, particularly reservoir engineering, production geology and evaluations, desires change. At present employed by major foreign company as superintendent of large fully integrated district. Married, 34 years old, excellent references. Code 152.

♦ Petroleum engineer, 32, single, five years' experience, desires change of employment for active position in drilling, completion and production. Would prefer employment in Texas. Code 153.

♦ August graduate in petroleum engineering, MS degree. Age 22, single, nonveteran, available August 10 for employment. About two years' non-engineering field and office experience. Will work anywhere. Code 151.

♦ Petroleum engineer, 31, six years diversified experience oil production, desires position demanding an aggressive, capable and responsible man. Available mid-September. All replies acknowledged. Code 154.

POSITIONS

♦ Applications now being received from petroleum, chemical or mechanical engineers with PhD degrees and petroleum reservoir engineering experience for teaching positions on the petroleum engineering staff of a Southwestern institution. Salary based on background. Initiative essential. Interviews during September. Appointments effective September 1. Consulting and research encouraged. Send recent photograph with data. Code 531.

♦ A southern university has an opening for a man to teach courses in petroleum and natural gas production engineering. It would be preferred that he have an MS degree, but this will be waived in favor of adequate experience. Rank and salary will be based on the qualifications of the candidate. Code 532.

Institute Finances Show $38,605 Gain Over 1950

Income of the AIME for the first six months of 1951 shows an increase of $28,405 from the same period in 1950, and expenses have been $10,200 less than a year ago. The net improvement is thus $38,605. Inasmuch as the Institute wound up the year 1951 with a deficit of $14,854, it would appear from present indications that for the first time since 1942 the AIME will end the year with a comfortable surplus without tapping any of the special funds. The net improvement over last year is even better than the preceding figures indicate because the expense of the Salt Lake City office of the Mining Branch is all currently being taken out of regular income whereas last year it was met by special appropriations.

Income from dues and initation fees in the first six months of 1951 totaled $279,173, compared with $269,776 in 1950; advertising, $67,430 ($51,163 in 1950); publication sales, $37,131 ($35,351 in 1950); other income, $5,361 ($4,397 in 1950); total, $389,094 ($360,689 in 1950). Expense for Local Sections, Divisions, and Meetings was $46,187 ($36,576 in 1950); library assessment and building rental, $9,867 ($12,362 in 1950); publications, $150,454 ($166,726 in 1950); general and administrative, $50,424; ($51,589 in 1950); total, $257,784 ($267,984 in 1950). ★ ★ ★

Proposed for Membership, Petroleum Branch

Total AIME membership on June 30, 1951, was 16,969; in addition, 2,502 Student Associates were enrolled.

ADMISSIONS COMMITTEE

Thomas G. Moore, Chairman; Carroll A. Garner, Vice-Chairman; George B. Carless, F. W. Hanson, Albert J. Phillips, Lloyd C. Gibson, R. D. Mollison, John T. Sherman. Alternates, A. C. Brinker, H. W. Hitzrot, Plato Malozemoff, Ivan Given, T. D. Jones, W. H. Farrand.

Institute members are urged to review this list as soon as the issue is received and immediately to wire the Secretary's office, night message collect, if objection is offered to the admission of any applicant. Details of the objection should follow by air mail. The Institute desires to extend privileges but does not desire to admit persons unless they are qualified. Objections on applications should be received on the 15th of the month following publication in PETROLEUM TECHNOLOGY.

In the following list C/S means change of status; R, reinstatement; M, member; J, Junior Member; A, Associate Member; S, Student Associate; F, Junior Foreign Affiliate.

CALIFORNIA

Taft — Berninghausen, Hubert E. (A); Bristow, Arthur B., Jr. (J); Hutchison, Stanley O. (J) (C/S-S-J).
San Diego — Kunzi, Robert E. (J) (C/S-S-J).

COLORADO

Denver — Shannon, Richard Stoll, Jr. (M) (C/S-A-M).

KANSAS

Moundridge — Temple, Horace L. (M) (C/S-A-M).
Wichita — Bickford, Christy R., Jr. (J) (R, C/S-S-J).

LOUISIANA

New Iberia — Pollard, Charles H. (M).
Shreveport — Lash, Wayne E. (A).

MASSACHUSETTS

Worcester — Carofanello, Alfred A. (J).

MINNESOTA

Jordan — Leibbrand, Donald C. (J).
Minneapolis — Becker, William H. (J) (R, C/S-S-J); Boyle, F. Richard (J) (C/S-S-J); Goodrich, John H. (J); Elletson, Francis M. (J) C/S-S-J).
Morris — Judd, George B. (J).
Winona — Griffith, Theophilus (J) (R, C/S-S-J).

MISSISSIPPI

Nicholls, Thomas C. (J) (R, C/S-S-J).

NEW YORK

Long Island — Schratwieser, John C. (J) (C/S-S-J).

OKLAHOMA

Clayton — Saye, John M. (J) (C/S-S-J).
Healdton — Talley, Martin L. (J).
Ketchum — Graham, Bill J. (J) (C/S-S-J).
Stillwater — Saxon, Robert K. (J) (C/S-S-J).
Tulsa — Amini, Khodagholi K. (J) (R, C/S-S-J); Kellogg, Walter N. (J); Swearingen, John E., Jr. (M) (C/S-J-M).

PENNSYLVANIA

Berwick — Dendler, Andrew W. (J).
Bradford — Halvorsen, Robert L. (J) (C/S-S-J).
DuBois — Heberling, Harold K. (J) (C/S-S-J).
Duke Center — Williams, James R., Jr. (J) (C/S-S-J).
Reading — Angstadt, Raymond R. (J) (C/S-S-J).
Tarentum — Wiggins, Ralph R. (M).

TEXAS

Beeville — Kates, James M. (J).
Big Spring — Smith, Mike O., Jr. (J) (R, C/S-S-J).
Corpus Christi — Chamrad, Daniel B. (M).
DeKalb — Wilson, Roger L. (A) (C/S-S-A).
Dallas — Aronofsky, Julius S. (J); Garber, Thomas B. (J) (C/S-S-J); McColloch, Lewis C. (M).
Fort Worth — Thomas, George L. (J) (C/S-S-J).
Houston — Brown, Charles W. (M) (C/S-A-M); Riggs, Thomas A. (J) (R, C/S-S-J).
Katy — Simmons, Marvin G. (J).
McAllen — Ely, Edgar L. (J) (C/S-S-J).

CANADA

Toronto, Ont. — Wilson, Eric D. (M) (C/S-A-M).

VENEZUELA

Caracas — Dean, Laroy, Jr. (J) (R, C/S-S-J). ★ ★ ★

Education for Research

(Continued from Page 13, Section 1)

trial trends and requires special abilities. Men who go on to the doctor's degree will, in general, possess these abilities. Normally they are selected from master of science graduates who have demonstrated particular capacity for advanced and original work.

As may be inferred from the previous remarks, education for research in petroleum engineering differs very little from education for research in any other branch of engineering. The backbone of research in engineering is engineering science.

It is evident that the most important requirement in a program of advanced study is a further intensified study of mathematics, including the tools of statistical analysis, the structure and properties of materials (solids, liquids and gases), and a thorough study of energy transformations as embodied in thermodynamics, heat and mass transfer and the flow of fluids and electricity.

The second most important consideration is training in research skills and techniques, which implies active participation in actual research work. This, incidentally, represents a type of training in which the engineering school effectively takes over some of the apprenticeship phase of the educational process. The student must develop ability to plan and execute experiments effectively. He must learn how to reduce his observations for analysis and how to interpret and correlate his results.

A third important consideration is for the student to learn the methods by which petroleum engineering science has been advanced, the general principles that have been established and an appreciation of some of the problems yet to be solved. This is the consideration in which "petroleum engineering" enters as a flavor of specialization. The student should include one or two courses or seminars dealing, for example, with petroleum reservoir mechanics and well logging, geophysics and petroleum petrography, or petroleum processing topics, depending upon individual circumstances.

Finally one should not conclude such a discussion as this without some remarks regarding the student. It has been assumed throughout this discussion that the student has ability. The training program outlined above will not necessarily restrict him to a career in research. The disciplines are such that he will be equally effective for service in design and application. For example, he would be well prepared to undertake work in reservoir analysis, bringing to it, as he gains experience, new and sounder methods. The basic material of education is the student. As may be inferred from previous remarks, the student who is to undertake this training must have abilities which are far from common. ★ ★ ★

Microfilms Available Of AIME Journals

A contract has been renewed with University Microfilms, Ann Arbor, Mich., for microfilming complete annual volumes of the three AIME monthly journals, including the Transactions sections. Microfilms of the 1950 volumes are now available from University Microfilms to those who receive the journals. The AIME receives a royalty of 10 per cent of the sales price. The microfilm record is available to libraries and others who wish to have a complete record stored in a minimum of space. ★

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Book Reviews

Oil and Gas Production

Compiled by the Engineering Committee, Interstate Oil Compact Commission, University of Oklahoma Press, Norman, 1951. 122 pp., illus., diagrs., charts, maps, tables, 9¼x6¼ in., cloth, $2.75.

This book explains in simple and concise terms the story of petroleum from its occurrence in natural reservoirs to its recovery through the most efficient technical methods. Designed to explain to the layman the basic principles involved in oil and gas production, the book presents numerous illustrations showing the nature of petroleum traps and the behavior of fluids under temperature and pressure changes. The book explains briefly but comprehensively the sources of energy involved in primary and secondary recovery, and gives field examples to demonstrate the efficiency of various production methods. Explanations of measurements in production and regulatory practices which affect oil recovery are also included.

Practical Oil Geology, Sixth Edition

By Dorsey Hager, McGraw-Hill Book Co., New York, Toronto, London, 1951. 589 pp., illus., diagrs., charts, maps, tables, 7½x5¼ in., leatherette, $7.50.

This newly revised edition adds new data on well sampling paleotectonics, well logging methods, and a section on Veatch's Rule, an approximate method for evaluating gas and oil potentials, to its basic material on geology and geophysics in previous editions. Arranged for easy reference, the book covers structural geology, discussion of oil and gas traps, methods of searching for gas and oil in untested areas, the selection of sites for testing, the application of geology in drilling and its use in production. Reference material on the relationship of water to oil, composition and origin of natural gas and gasoline, and analyses of oil shales is also included.

Structural Geology of North America

By A. J. Eardley, Harper and Bros., Publishers, New York, 1951. 624 pp., diagrs., charts, maps, 8½x11½ in., cloth, $12.50.

A complete geological history, this book describes the crustal unrest of the North American continent in post-Proterozoic time. It covers the formation and constitution of mountain systems, basins, arches, and volcanic archipelagos; the beveling of the highlands; and the filling of the basins. The whole procession of deformational and sedimentary events is chronicled, together with the major supporting evidence. The unusual double-column page size permits larger maps, cross-sections and other drawings than would otherwise be possible. Sixteen paleotectonic maps in full color are included in the many illustrations. The author is chairman of the Geology Department of the University of Utah, and has done consulting work in petroleum exploration.

Oil in Brazil

By Joseph E. Pogue, The Chase National Bank, New York, 1951. 32 pp., charts, maps, tables, 9 x 6 in., paper.

With growing petroleum requirements, bolstered by population growth, industrialization and increasing imports of machinery and automotive equipment, Brazil may find it necessary to expand its production, rather than depend on imports. The author, petroleum consultant for the Chase National Bank, presents his views for legislation to encourage Brazil's petroleum development under a competitive system. ★ ★ ★

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